

AN ENGINEERING STUDY OF THE DRIFTWOOD-BENEZETTE  
GAS FIELD IN PENNSYLVANIA

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## An Engineering Study of the

# Driftwood - Benezette Gas Fields

## In Elk, Cameron, and Clearfield Counties of Penna.

By Commander C. B. Connally\* and P. F. Fulton\*\*

### I. Introduction

This paper presents a petroleum engineering approach to the evaluation of production practices employed in the Driftwood-Benezette gas field in Pennsylvania, and compares the results of such practices with those which might have been accomplished had the field been developed and operated in the most efficient manner, or in accordance with modern petroleum conservation laws.

The Driftwood-Benezette gas field is important to this study only in that it provides a means for illustrating production practices generally employed in all Pennsylvania gas fields. Therefore, no attempt has been made to set forth details of engineering and geologic interest not closely related to production practices.

Petroleum production practices in Pennsylvania have remained the same in principle since the discovery of the Drake well in 1859. There are no laws restricting petroleum production even though it is a well known fact that "wide-open" flow may cause great underground losses of oil or gas; moreover, there are no laws protecting landowners' correlative rights—the right to enjoy the use of one's property so long as this enjoyment does not do injury to others.<sup>1</sup>

There have been several proposals<sup>2</sup> for petroleum conservation laws which would require or encourage the development and operation of a petroleum reservoir as a single unit rather than on the wasteful and costly basis of "every man for himself." None has been enacted, however, and it appears that Pennsylvania may become the leading oil and gas producing state where no such laws are in effect. It is indeed a mystery why no such laws have been enacted. One would think that Pennsylvania, the founding state of the petroleum industry, would have been a leader in petroleum regulatory law. There must be some merit to petroleum conservation and unitization laws, for no state has ever repealed such a law. The Interstate Oil Compact Commission, which through engineering, research, and other committees functions to advise the various states on petroleum regulatory measures, has recommended the enactment of a unitization law.<sup>3</sup>

Does it not seem logical that there should be a minimum waste of petroleum resources, and that a landowner should be permitted to recover his fair share of the oil or gas underlying his land, and only his fair share, without the drilling of unnecessary wells?

Perhaps many Pennsylvanians are not acutely aware of the waste of their petroleum resources or the infringement on their correlative rights caused by maximum-rate production practices employed in Pennsylvania. This study has been made in an attempt to illustrate, quantitatively, the effects of such practices as they relate to natural-gas production.

The Driftwood-Benezette field provides a good example for illustrating natural-gas production practices in Pennsylvania. This field was intensely drilled soon after its discovery and allowed to produce at maximum rate. Each landowner had to get his gas to the surface before his neighbor drained it away. It is the authors' opinion that this caused the drilling of about 200 more wells than would have been necessary to produce the field efficiently, and that open-flow production will cause the underground loss of at least 20 billion cubic feet of gas, with a net value of approximately \$2,000,000.

Unfortunately, accurate results cannot be obtained from the data available. Throughout this study, however, the authors continually strove to favor the use of results and assumptions which would not exaggerate the adverse effects of existing production practices.

### II. Inadequacy of Engineering Data

It became apparent at the beginning of this study that the lack of petroleum regulatory laws has resulted in an inadequacy of engineering data.

It is impossible for engineers to make accurate engineering studies, upon which plans for future gas production, transportation, storage and marketing must be based, without complete and accurate engineering information. Furthermore, this information must be readily available, at a central source, to all interested parties.

In 1935 the Bureau of Mines introduced a method for computing gas-well capacities and for applying this information to production practices.<sup>4</sup> The basic equation<sup>5</sup> set forth in that report

is used throughout the natural gas producing industry—even in Pennsylvania—yet the data available on Pennsylvania wells for use in that equation are entirely inadequate for accurate calculations.

Though there are no laws preventing operators from obtaining these data on their own wells, few will voluntarily close in a well or restrict its production while their neighbor drains gas from under their land at a maximum rate. Further, in order to provide maximum benefit, this information must be standardized and compiled under a well organized program, enforced by a central authority and maintained readily available at a central source.

This lack of adequate information has obviously lead to inaccuracies in much of the data that have been obtained. Probably the greatest inaccuracies have been in measuring the shut-in pressures of the wells, the very heart of the information used in petroleum engineering studies.

Another source of difficulty to an engineer is the confidential nature of production information on privately owned wells. An accurate evaluation of a well's performance requires the comparison of that well with other wells in the near vicinity, and an evaluation of the reservoir as a whole may require the use of performance data on any well in the reservoir.

Specific examples of either inadequate or inaccurate information encountered during the course of this study are listed as follows:

1. Shut-in well pressures are often inaccurate. Most wells were shut in for less than 24 hours when their pressures were recorded, some for only an hour or less.
2. The entire reservoir has never been shut in and the average pressure recorded, nor are individual wells shut in periodically for this purpose. One accurate reservoir pressure, after sufficient gas had been produced to show a pressure decline, would have been sufficient to compute total gas reserves. As the situation stands, operators are merely guessing at gas reserves, and no one will ever know how much gas is lost due to production practices.
3. Production information on privately owned land is confidential and, there-

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best advantage its resources of men and materials.

#### Acknowledgement

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## Wrather Retires As Director Of U. S. Geological Survey

Dr. William Embry Wrather, who recently retired as Director of the Geological Survey "has guided Survey Activities through 12 years of growth in service to the Nation during the difficult years of war and the later period of adjustment to an expanding economy," according to Secretary of the Interior Douglas McKay. Dr. Wrather was appointed in 1943, at a time when heavy demands were being made on the Survey for emergency services to the Nation in the midst of a world war.

Born in Kentucky and a graduate of the University of Chicago in geology and law, Dr. Wrather brought to the Survey a unique combination of administrative abilities gained through years of experience in the petroleum industry.

In 1954 he was given the 50th John Fritz Medal, and cited as "a geologist of worldwide experience and fame; an outstanding scientist and historian; a wise leader distinguished for his service to the Nation."

Under Dr. Wrather's leadership much progress was made in various facets of the science of hydrology and in the accumulation of basic water facts.

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Fig. A

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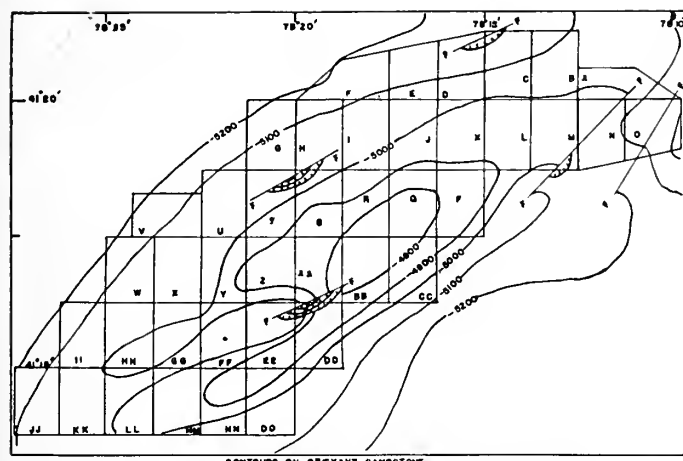


Figure 1—Structure Map, Driftwood-Benezette Gas Field

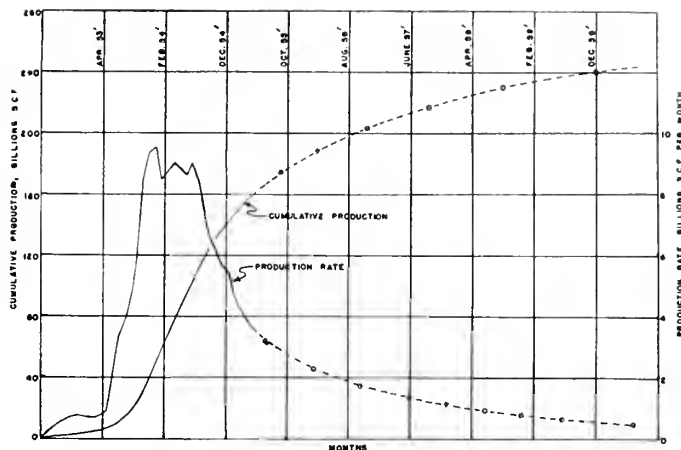


Figure 3—Cumulative Production and Production Rate vs. Time

fore, not available to the public or to all interested producing companies.

4. No records could be found showing shut-in pressures for wells on more than one occasion after having been cut in to the pipeline. This information is necessary in order to determine a well's performance characteristics and behavior as described in Section V, A and B.

5. No one producer or regulatory body has all the data on all the wells in the reservoir. Absence of monthly production rates for all wells is the most important example of this inadequacy. Other missing information might be as follows: The drilling method used, whether or not a well was shot, original well-head pressures and shut-in time, and whether or not a well had been abandoned.

6. The reservoir temperature has never been measured.

7. Very few reservoir sand thicknesses have been recorded.

8. Well locations are not recorded in a standard form.

9. Neither the porosity nor the permeability of the sand has ever been measured.

In view of the above, the results brought out in this study are not nearly so accurate nor significant as they otherwise might have been. Perhaps the inadequacy of this study will serve to indicate the necessity for such state statutes as will provide for the compilation of information necessary to conduct accurate engineering studies.

### III. History of Operations

#### A. The Reservoir

The Driftwood-Benezette gas field is the largest known gas field in Pennsylvania, covering about 42,000 acres in Elk, Cameron, and Clearfield Counties. Production is from the highly faulted Oriskany sandstone, which in this area is mostly "medium-grained, light gray,

quartzose, slightly calcareous."<sup>10</sup> The Oriskany is capped by the Onondaga limestone formation.

Figure 1 shows the approximate area of the reservoir superimposed on a contour map on the Oriskany sandstone as constructed by Fettke.<sup>7</sup> Figure 2 shows locations of all wells numbered in the sequence in which they were completed or drilling operations abandoned, although numbers for dry holes have been omitted on the drawing.

It should not be construed that the reservoir has such a jagged boundary as is indicated by the block areas in Figures 1 and 2. These blocks established by the authors were used to compute the average reservoir pressure as described in Section IV.

This field is located on the Driftwood anticline, the highest point on which is the Driftwood dome, located about one mile northeast of the town of Driftwood. This dome is not shown in Figure 1

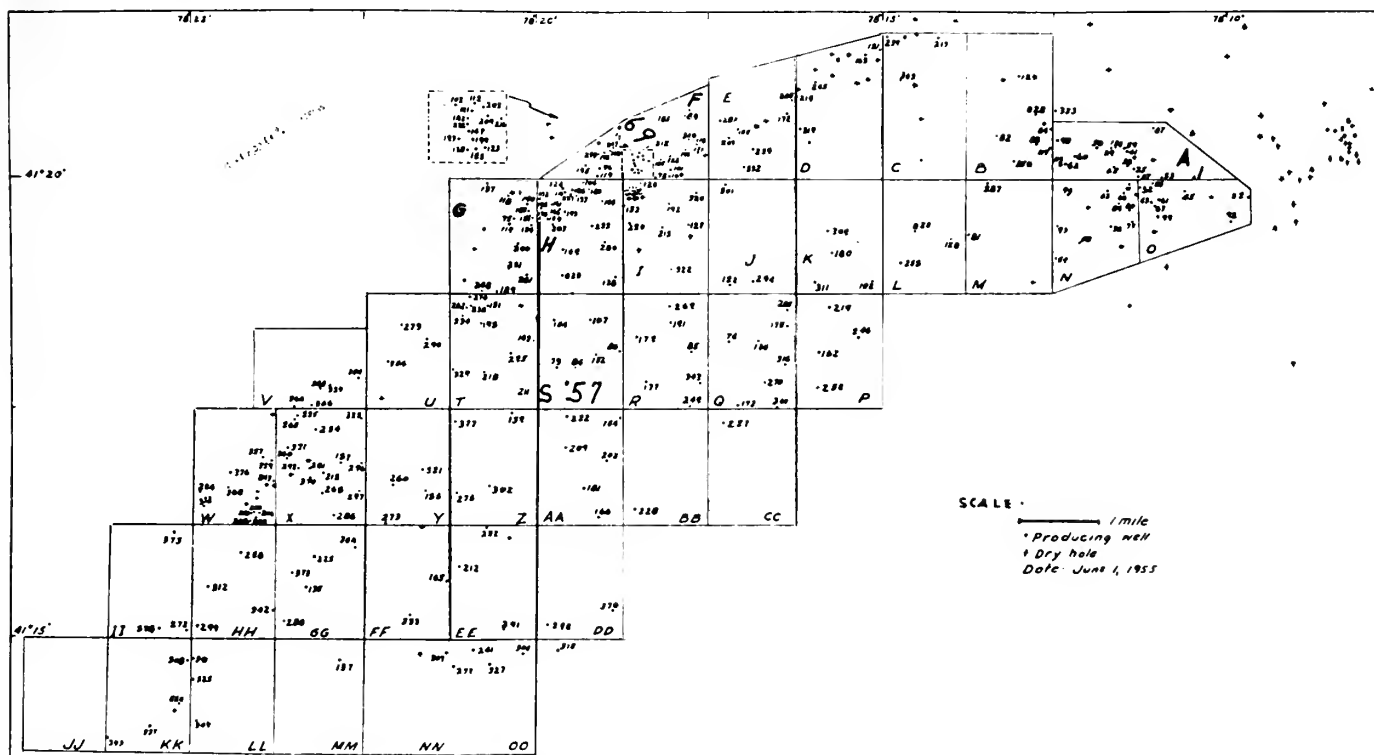


Figure 2—Block area map, Driftwood-Benezette Gas Field

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Fig. 107AA

Fig. 107

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since the dome itself proved to be outside the productive boundary of the reservoir, as indicated by the numerous dry holes shown just to the northeast of the reservoir in Figure 2.

The northeast or Driftwood end of this reservoir was discovered first. The discovery well was Sylvania's S. C. Eaton No. 1 (Figure 2, well 1-A) completed September 15, 1951. Since this well was situated relatively low on the southwest plunge of the Driftwood dome, subsequent tests were made high on the dome in and around the town of Driftwood, none of which proved productive apparently because of a tight sand stratigraphic closure at the northeast end of the reservoir. Development was then shifted down the plunge to the southwest.

The Keta Oil and Gas Company's Charleroi Mountain Club No. 1 (Figure 2, well 57-S) on the Benezette dome opened the Benezette end of the reservoir in December, 1952. Then in March, 1953, the Benezette Valley Development Company brought in the William Woodring No. 1 (Figure 2, well 69-F). This well was extremely important in that it is some 300 feet lower on the flanks of the Benezette dome than the Charleroi well, indicating that the Driftwood-Benezette field was much larger than had previously been estimated.<sup>8</sup> This led to the furious drilling race between private landowners which resulted in the dense well pattern as shown in Figure 2, areas F, G and H. Presumably, if the areas to the south had not been mostly state-owned land, the entire field would have been drilled into a similar pattern.

## B. Drilling and Production Practices

### 1. Drilling and Gauging

Drilling operations reached a peak in August, 1953, when 22 producing wells were brought in. The rate then dropped slightly and leveled off at about fifteen to twenty wells per month until July, 1954, at which time there began a rapid decline in the drilling rate.

Most of the early drilling was with cable tools which averaged about sixty feet per day. Rotary drilling was later used, which averaged about 180 feet per day; however, lost circulation and completion problems were frequently caused by the high density (17 pounds per gallon) drilling mud. Completion problems were often overcome by drilling-in with cable tools, but a more recent practice of using air-rotary drilling with gas completions has been highly successful in eliminating both of these difficulties. The air-rotary has shown a penetration rate of about twice that of the regular rotary.<sup>9</sup>

All methods employ the practice of setting a seven-inch O. D. casing about ten feet into the Onondaga limestone, and then drilling a 6 $\frac{1}{4}$ -inch hole into or through the Oriskany sandstone.

Open-flow capacities of wells are measured with pitot tubes while the gas is discharged to the atmosphere. Shut-in pressures are generally recorded after

wells have been closed in for 24 hours, although the rush to cut the wells into the pipeline frequently permits only a few hours shut-in time.

### 2. Production Practices

Little can be said of production practices except that wells are cut in to the pipeline as quickly as possible and permitted to flow at maximum rate. Figure 3 shows the cumulative production and production rate of the field plotted against time. The dotted portion of the curves represents the predicted recovery and recovery rates as explained in detail in Section V, C.

There has been no evidence of water drive during production from this field.

There have been occasions of wells being drowned out by water, but this difficulty has frequently been relieved, at least temporarily or partially, by shutting in the wells for a few days.

### IV. Determination of Reserves

An accurate determination of gas reserves in a reservoir can be made only when accurate reservoir pressures are known. Since the Driftwood-Benezette reservoir has never been shut in in order to determine a reservoir pressure, and since pressures for individual wells are not periodically recorded, any method used in computing reserves is largely guesswork. The original pressure was most probably about 4,020 pounds per




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square inch gage, as measured at the well head. Obviously, no other pressure would be needed to compute reserves if the boundaries of the reservoir, the porosity, the per cent water saturation, and the sand thickness were known. However, in view of the highly faulted structure of this reservoir, the probable wide variation in porosity, and the doubtful boundaries as estimated, the only practicable method for determining reserves is by the use of declining reservoir pressures with cumulative production, as is shown graphically by Figure 4, and as explained in detail later in this section.

The only course for determining the average reservoir pressure lay in averaging pressures by areas, area pressures being obtainable from original pressures for new wells. It is believed that the boundaries of the reservoir are sufficiently well established so that it can be divided into areas as shown in Figure 2, and that each area has roughly the same average porosity and sand thickness. Though this may not be entirely true, the method of averaging area pressures in order to determine the over-all reservoir pressure is not overly demanding of an accurate reservoir area, and it is not necessary that the sand thickness or porosity be known, provided each area is assumed to have equal pore space. The reservoir area as shown is comprised of forty-one approximately equal-sized blocks of about one thousand acres each.

The only difficulty lay in determining the average area pressures at a selected date or dates. The pressure recorded for a well drilled in the area on or near the selected date could not be used with any degree of accuracy, for often the well would be in such close proximity to another that its pressure would be greatly affected, or the pressure shown for a well drilled at a later date in the same vicinity might have been considerably higher. Many additional factors had to be considered, such as the location of the wells in the area, their distance apart, the length of shut-in time compared to flow rate, and pressures in adjoining areas.

It soon became apparent that many

recorded well pressures were lower than they should have been. Most of the wells were shut in for less than twenty-four hours when their pressures were recorded. This is far short of the time estimated to have been necessary for the pressure to stabilize in sand of such low permeability. It has been illustrated that pressures recorded after three days may still be well below the stabilized pressures.<sup>10</sup>

It was impossible to select any single date near which, during the early and late stages of development, wells were drilled in a majority of the areas. This

required such an extensive use of estimated area pressures that little reliability could be placed in the computed average. It was, therefore, decided to determine the one most accurate average reservoir pressure which occurred well along in the productive life of the reservoir. Only one pressure, other than the original, is needed to compute reserves, and one good pressure is considered to be more accurate than a decline curve average of several poor ones. In order to determine the most accurate pressure each block area was considered separately. Again, weighing all significant

FIGURE 6. AVERAGE WELL FLOW RATE DECLINE

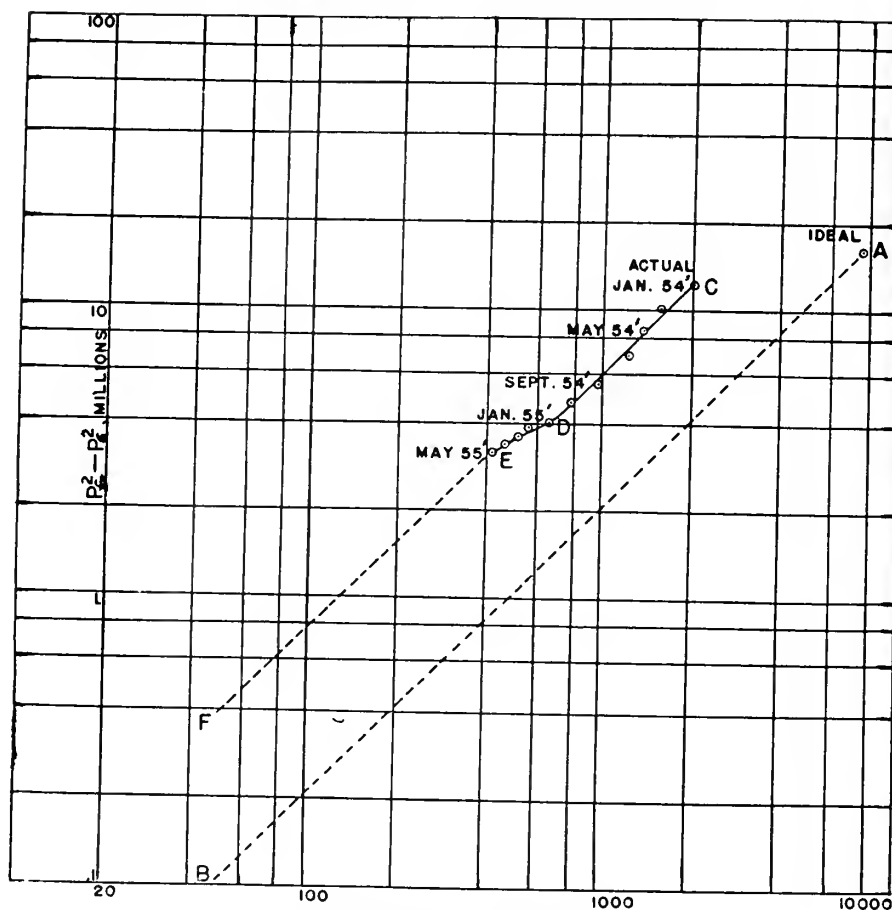


Figure 6—Average Well Flow Rate Decline

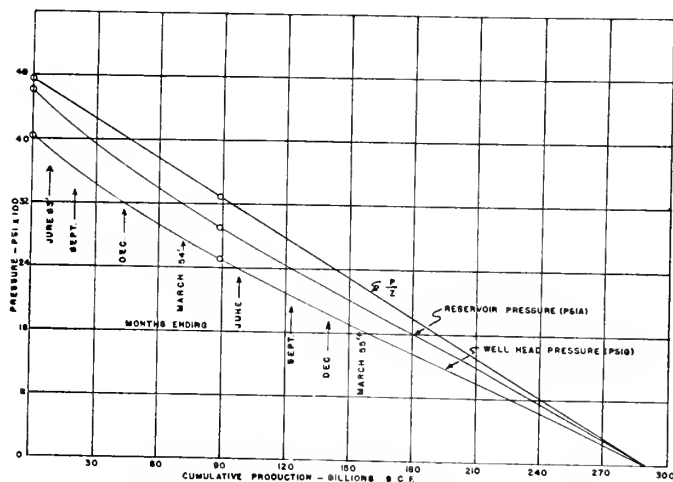


Figure 4—Pressure Decline with Cumulative Production

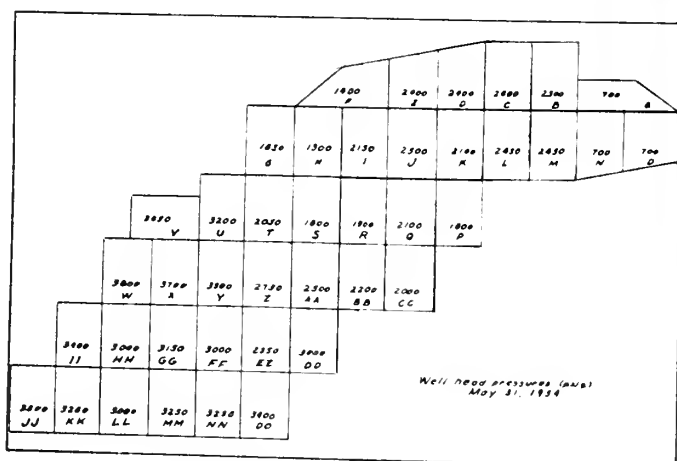


Figure 5—Pressures by Block Areas

factors stated above, every instance in which a well pressure or several well pressures appeared to reasonably represent that for the block area was recorded under the date shown. When such pressures for all areas had been recorded, the widest coverage of area pressures fell near the date of May 31, 1954. That date was, therefore, selected for determining the over-all average reservoir pressure. In cases where a block area failed to show a pressure on or near that date, it was possible to interpolate between dates on either side of May, 1954, or to estimate the area pressure from those shown for surrounding areas. Well-head pressures thus determined are shown in Figure 5. The average of these gage pressures came to 2,490 pounds per square inch.

The pressure due to the weight of the column of gas was computed using the equation

$$P_w = \frac{P_z R T 144}{M H} - .5 P_x^*$$

where

$P_w$  = well-head pressure in pounds per square inch absolute.

$P_x$  = pressure due to the weight of the gas column in pounds per square inch,

$Z$  = gas compressibility factor at average temperature in the well bore and at well-head pressure,

$R$  = gas constant,

$T$  = average temperature of the gas column,

$M$  = molecular weight of the gas,

$H$  = average depth of the reservoir below the surface.

If natural gas expanded upon release in pressure exactly in accordance with Boyle's law, the pressure decline curve would merely be a straight line through the original reservoir pressure and the May 31, 1954 reservoir pressure plotted against cumulative production as of May 31, 1954. However, since natural gas does not conform exactly to Boyle's law, the compressibility factor had to be considered. Calhoun shows that reservoir pressure ( $P$ ) divided by the compressibility factor for the gas ( $Z$ ) at reservoir conditions will plot as a straight line against cumulative production.<sup>11</sup> Compressibility factors were, therefore, computed for the two above reservoir pressures and a straight line plot made between the two  $P/Z$  points thus determined. The accuracy of the curve was checked analytically and original gas calculated to be 289 billion standard cubic feet. The reservoir pressures as they would be measured both in the reservoir and at the surface (Figure 4) were computed from the  $P/Z$  curves, using compressibility factors and values for the pressure due to the weight of the gas column as are shown graphically in Figures 7 and 8.

The 289 billion standard cubic feet of gas, as calculated to have been originally in the reservoir, at first appeared high, considering the present low production rate from the wells. An additional cal-

culation was, therefore, made to determine the porosity of the sand, using 42,000 acres which has been estimated as the area of the reservoir, and an average sand thickness of 17 feet as estimated from the few well records showing this information. The porosity thus calculated came to 4.18 per cent. This porosity certainly does not appear to be excessive, considering the nine per cent and 8.34 per cent porosities found, respectively, for Oriskany sand samples blown from wells in the Tioga<sup>12</sup> and the Leidy gas fields.<sup>13</sup>

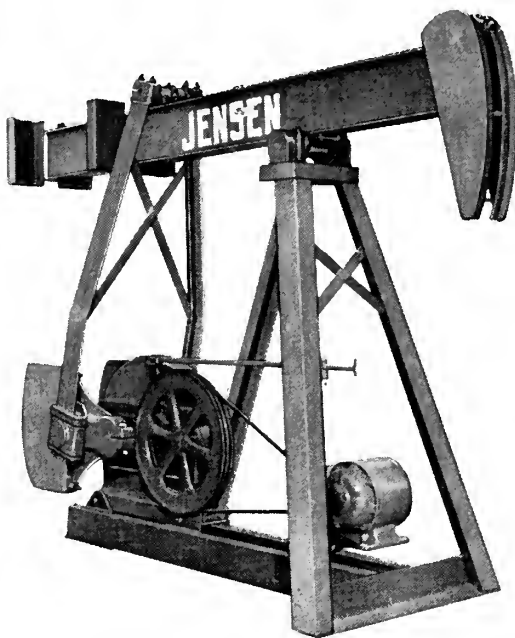
In consideration of the above, the 289 billion cubic feet does not appear to be excessive. An additional similar calculation of reserves was made, however,

using the absolute minimum feasible pressures for block areas as of May 31, 1954. This calculation showed 255 billion standard cubic feet as the original gas content of the reservoir. The original calculation is considered to be the more accurate.

## V. Operations

### A. Determination of Average Well Productive Capacity

The equation  $Q = C(P_r^2 - P_w^2)$  as described in the Bureau of Mines Monograph 7 is also applicable to groups of wells.<sup>20</sup> The average well productive capacity coefficient,  $C$ , may therefore be obtained by averaging the  $C$ 's computed for each well by dividing  $Q$  by  $(P_r^2 - P_w^2)^{1/2}$ . Values for  $Q$  and for  $P_{wh}$  are known as



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each well is completed and an open flow test is made. Since the value of  $n$  was not known, it was necessary to average the production rates ( $Q$ ) for wells producing under the same ( $P_i^2 - P_s^2$ ). Further, since little confidence could be placed in the accuracy of the lower pressures, it was decided to use wells showing well-head pressures near 3,500 pounds per square inch. Thirty such wells showed an average  $Q$  of 7,300M cubic feet per day. The pressure due to the weight of the column of gas in these wells averaged about 500 pounds per square inch, bringing the  $P_i$  value to 4,000 pounds per square inch. Since  $P_s$  can be neglected for these large-hole high-pressure wells flowing against atmospheric pressure, 7,300 ( $Q$ ) can be plotted against 16,000,000 ( $P_i^2 - P_s^2$ ) on

logarithmic paper as is shown by point A in Figure 6. This gives one point on the logarithmic plot, but does not of course show the slope of the line which can be used to determine values of  $Q$  at different values of ( $P_i^2 - P_s^2$ ). It was decided to use an  $n$  value of one (viscous flow) in order to simplify calculations and to preclude the exaggeration of the adverse effects of production practices as is brought out in Section V, B and C. Using this  $n$  value of one, the coefficient ( $C$ ) for the 30 wells came to .456. These values of  $C$  and  $n$  were justified by an average value of  $C$  equal to .45 for 127 wells on which the recorded data appeared to be the most accurate. The value of  $C$  for each individual well in this case was obtained by dividing the flow rate ( $Q$ ) by ( $P_i^2 - P_s^2$ ),  $P_i$  being the

closed-in individual well-head pressure plus the pressure caused by the weight of the gas column, and  $P_s$  again neglected.

Readers might be interested in the calculation of average permeability where the value of  $C$  equal to .456 was substituted in the Darcy's law radial flow equation for viscous flow. Though a rough assumption had to be made for the drainage radius and though the flow may not be considered as radial in all cases, the computed permeability of 4.05 millidarcies as compared to the estimated permeability of ten millidarcies tends to substantiate the assumption that the value of  $C$  is not excessive. Two samples blown from wells in the Leidy gas field averaged 10.9 millidarcies.<sup>21</sup>

In consideration of the above, the curve AB in Figure 6 may be considered to represent the production rate that could have been expected from the average well with decreasing values of ( $P_i^2 - P_s^2$ ) had the physical characteristics of the well and the producing formation remained constant, and had the wells been so spaced as to have the average formation pressure acting on each well.

#### B. Effect of Well Spacing and Production Practices on Production Rate

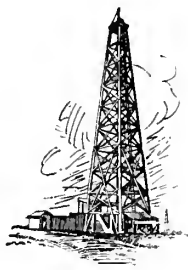
As pointed out in the previous section, curve AB (Figure 6) represents the declining production rates with declining ( $P_i^2 - P_s^2$ ) values that could have been expected from average, undamaged, properly spaced wells. Curve CD (Figure 6) represents the actual average production rate per well with declining average reservoir pressures as shown in Figure 4. Points on curve CD were determined by dividing the total monthly production rates by the average number of producing wells as of the date indicated and plotting these rates per well against the ( $P_i^2 - P_s^2$ ),  $P_i$  being considered as the formation pressure shown by Figure 4 and  $P_s$  being dependent upon the line pressure and is estimated as 600 pounds per square inch. The deficiency in production rate per well for any value of ( $P_i^2 - P_s^2$ ) is represented by the horizontal distance between the two curves. This loss can be attributed to local pressure depletions in densely drilled areas and to physical damage to wells brought on by the rapid production rate.

Production losses caused by water coning, well caving, etc., cannot be well illustrated from the data available, although it would be a simple procedure to shut in wells occasionally and to plot the  $Q$  versus the ( $P_i^2 - P_s^2$ ) on logarithmic paper. A line through successive points thus obtained would indicate whether or not a well is being damaged. A curve that bent toward the pressure axis would be indicative of water coning or other factors hindering deliverability. If only two points are available, and a line through the two points has a slope greater than one (more than 45 degrees to the pressure axis), it will, in the authors' opinion, be indication of well damage. This procedure was attempted for the few state wells on which records

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could be found showing shut-in pressures sometime after their original gaging. However, curves thus obtained only served to prove the inadequacy and inaccuracy of recorded data. One curve showed a reverse slope, indicating lower flow rate with increasing formation pressure.

The Bureau of Mines back-pressure method for analyzing the deliverability of gas wells is a much more thorough and detailed procedure than that described above. Far greater benefits than that discussed above may also be derived from their method, although it requires the restricting of a well's flow for considerably more time than production practices in Pennsylvania permit.

### C. Estimated Losses in Ultimate Recovery

Although it is impossible to predict the ultimate gas recovery from this reservoir with any degree of accuracy, it is fairly obvious in view of the declining production rate that an uneconomical production rate will be reached long before 289 billion cubic feet of gas have been produced.

Curve DE, Figure 6, shows a recent increasing rate of decline in production rate. This may be due to a variety of factors, such as

1. Water fingering cutting off relatively high pressure gas zones.
2. Water coning near the well bore, reducing the effective sand thickness.
3. Water condensation, reducing the effective permeability to the gas.
4. Water accumulation in the well bore.
5. Well caving.
6. Structural conditions within the reservoir.
7. The temporary shutting in of an increasing number of wells (since the rate is based on the number of producing wells as drilled rather than the actual number in operation).
8. Almost total pressure depletion in densely drilled areas.

It is the authors' opinion, however, that conditions in the reservoir may soon stabilize and that the flow rate after that time will continue in a directly proportional relationship with  $(P_i^2 - P_s^2)$ ; at least this is the best that can be expected. This is illustrated by the curve EF, Figure 6. Though there is little chance that this curve will hold true to the abandonment date, it is not unreasonable to expect that it will hold approximately true for the next few years. This curve may be used in conjunction with the reservoir pressure curve (Figure 4) to provide a trial and error means for predicting future production and production rates. The dotted portions of the curves (Figure 3) were derived in this manner, considering a gradually decreasing value of  $P_i$  to zero in the year 1959. By the end of the year 1959 there should have been about 240 billion cubic feet of gas produced from this reservoir.

In consideration of curves AB and EF (Figure 6) and assuming a minimum economic flow rate ( $Q$ ) of 50MCF per day at zero back pressure ( $P_s$ ), the reservoir could be expected to be abandoned at an average pressure ( $P_i$ ) of 632 pounds per square inch, whereas in the "ideal" case the abandonment pressure would be 316 pounds per square inch. This, according to Figure 4, reflects a loss of about 22 billion cubic feet of gas due to inefficient production practices.

Actually, it is anyone's guess as to just how far into the future this reservoir will produce gas at an economic rate. Most likely there will be numerous wells capable of producing gas at an economic rate for many years to come.

It is highly probable, however, that water fingering and coning has or will cut off relatively high pressure zones within the reservoir, and that a reduced effective permeability to gas caused by water coning and condensation will seriously curtail production and reduce the ultimate recovery. An estimated loss of approximately 20 billion cubic feet of gas is considered to be conservative.

### VI. Evaluation of Results

#### A. Operational Aspects

Although this study has developed no absolute proof that there will be substantial losses in ultimate recovery of gas from this reservoir, it does indicate that such losses are very likely and pre-

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sents definite proof that a great amount of manpower and materials have been unnecessarily expended. Curves AB and CD (Figure 6) show that actual production per well was only about 35 per cent of what might have been expected from the properly-spaced average well. or that about one-third of the wells, if properly spaced and undamaged, should have given the same production rate. As was pointed out in Section V, A, this figure is based on a conservative estimate of the slope of the logarithmic curve AB (Figure 6) equal to one. It is possible that this curve could have had a slope of less than one, showing an increasingly wide separation between the "ideal" and "actual" curves with decreasing pressures, and therefore an increasingly poorer comparison of the actual well production rate with that of the ideal.

The ideal number of wells can only be determined by an economic balance of a great many factors, such as recoverable gas in place, drilling costs, back pressure required to prevent damaging the well or the producing formation, market demands and commitments and others. The back pressure required can be determined accurately by the Bureau of Mines method, but even this is subject to economic considerations. It may, for example, be more economical to permit minor damage to the well than to hold the back pressure sufficiently high to prevent damage entirely. Some states force the application of back

pressure by restricting gas production to 25 per cent of open flow capacity. However, this restriction is also intended to prevent gas production in excess of market demands, and there is no reason known to the authors why Pennsylvania should restrict production to this rate if it can be shown that significant damage will not occur to wells producing at higher capacities. All of the above factors can best be weighed and applied through a unit operation plan, assisted perhaps by a well-spacing regulation.

It is probable that no more than two billion cubic feet per month would have been the ideal production rate from the Driftwood-Benezette field. Gas companies taking gas from this field must contract for vast quantities of gas from the Southwest to meet commitments during the winter months. Furthermore, the nature of pipeline operations as well as economic factors in the producing Southwest demand the establishment of long-term contracts with little or no seasonal variations in gas deliveries. This requires the delivery of large quantities of gas to this area during the summer months which must be stored in underground reservoirs. It is therefore obvious that the most economical rate to extract gas from this field would be a long-term rate necessary to augment deliveries from the Southwest with a minimum of storing required.

According to curve AB (Figure 6), two billion cubic feet per month could have been produced early in the productive

life of the field ( $P_i = 4,600$ ) with 27 wells producing at 25 per cent of open-flow capacity, and with 100 wells at this capacity five years later when the 120 billion cubic feet produced would have caused the reservoir pressure to drop to about 2,400 pounds per square inch (Figure 4). At 50 per cent open-flow capacity, only half of these wells would be required, and 100 wells would produce two billion cubic feet or more per month until 175 billion cubic feet of gas had been produced. Assuming that the flow rate could reach a maximum at the lower pressures without causing significant damage to the wells or the formation, 100 wells would sustain the 2 billion cubic feet per month rate for almost nine years or until 210 billion cubic feet of gas had been produced. Does not this appear more efficient and logical than has been the actual practice of drilling around 300 producing wells to obtain the flow rate shown in Figure 3?

The above comparison of actual practices with those which might have been employed under unit operations or under well spacing regulations does not show a comparison of ultimate recovery losses. It was illustrated in Section V, C that there should be at least 20 billion cubic feet of gas lost because of inefficient production practices. Though structural conditions in the reservoir might not permit such high ultimate recovery in either the actual or the ideal case, it is probable that unit operations or ade-

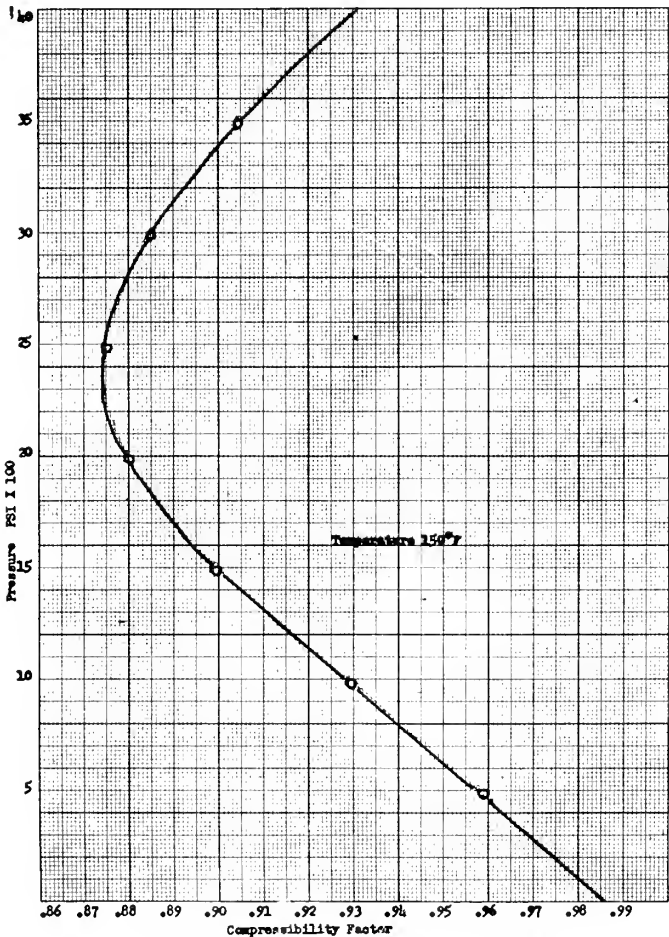


Figure 7—Compressibility factor vs. Pressure

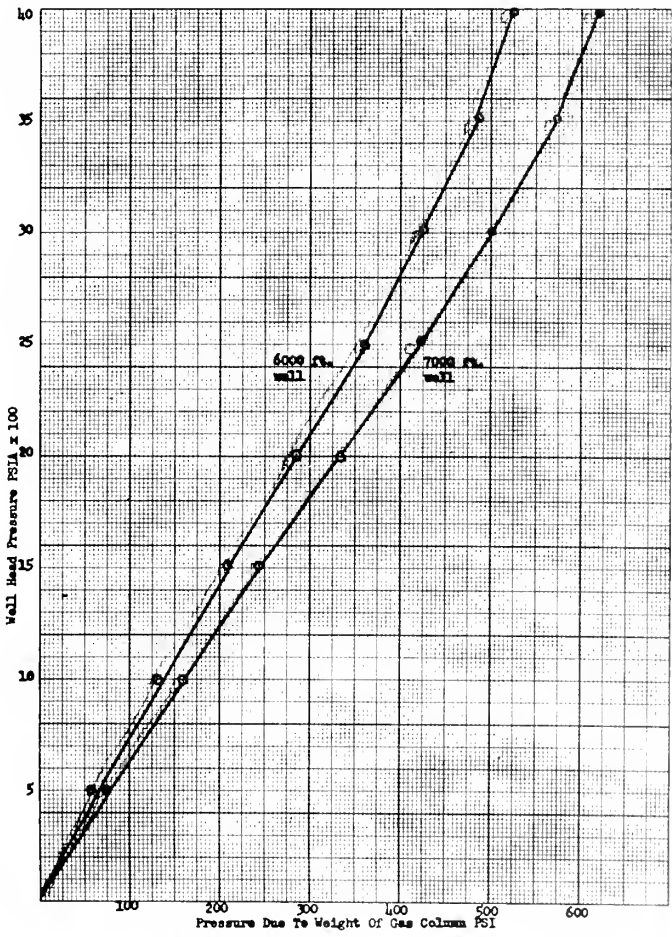


Figure 8—Pressure due to weight of gas column of well-head pressure



quate well spacing regulations would provide for more efficient exploration and thereby for a production rate closely approaching that shown by the curve AB (Figure 6).

## B. Economic Aspects

### 1. General

The economic aspects of production practices may be illustrated roughly as follows:

(a) Before this reservoir is abandoned there will probably have been 300 producing wells drilled—200 more than is conservatively estimated to be the ideal as stated in the previous section. At \$75,000 per well, this will amount to an unnecessary expenditure of \$15,000,000.

(b) It is estimated that at least 60 billion cubic feet of gas will have been stored and re-extracted beyond that which would have been necessary at the two billion per month rate. At an estimated cost of five cents per thousand cubic feet for storing and re-extracting, this will amount to \$3,000,000.

(c) Twenty billion cubic feet of gas estimated to be lost due to open flow production practices, at an estimated net value of about ten cents per M cubic feet<sup>22</sup> will amount to a loss of \$2,000,000.

(d) It is estimated that about 75 billion cubic feet of gas would have increased in value by at least two cents per M cubic feet had it been possible to produce this gas on a seasonal contract or at a slower rate. This will amount to \$1,500,000.

(e) There have been numerous relatively minor excessive expenditures, such as expenses for operating compressor stations, additional well maintenance costs due to open flow production practices, excess gathering lines, etc.

In view of the foregoing illustration, it is reasonable to assume that \$20,000,000 have or will be wasted by the production practices employed in the Driftwood-Benezette gas reservoir. Furthermore, a large portion of these losses will be paid by the consumer in the form of high gas prices or in taxes to make up for the losses from state-owned tracts.

### 2. Private Landowners

Much of the land overlying this reservoir is privately owned small tracts of one acre or less. Such a landowner's fair share of the gas, considering 40,000 acres total and 280 billion cubic feet of gas as recoverable, is 7,000 M cubic feet. At one-eighth royalty this figure is further reduced to roughly 900 M cubic feet, which would amount to \$247.50 at the current price of 27½ cents per M cubic feet. It is conservatively estimated that many small tract landowners have or will receive at least a hundred times this figure. Their excess profits obviously resulted in losses from less densely drilled areas, which in this field are mostly state-owned tracts.

### Conclusion

It is concluded that there have been about 200 excess wells drilled in the

Driftwood-Benezette field; that there could not possibly have been a fair and equitable distribution of the gas among the various landowners; that very probably there have or will be large quantities of gas left in the reservoir because of open-flow production practices; that sound engineering principles are not observed in gaging wells and in evaluating their performance, and that all of these are directly attributable to the lack of petroleum regulatory statutes in Pennsylvania. It is further concluded that the general public supports a large share of the inequities, gas losses and excess expenses either in higher gas prices or in decreased revenue from publicly owned land.

The obvious recommendation, therefore, is that the citizens of Pennsylvania demand the enactment of state statutes which will prevent this waste of manpower, materials, and petroleum resources, and which will insure the protection of correlative rights of landowners.

The details of the varied petroleum conservation measures and unitization statutes are beyond the scope of this paper. The average citizen, however, should not be so much concerned with these details as by the fact that nothing is being done to remedy the current inefficient and unfair production practices. Citizens should place their faith in an Oil and Gas Committee appointed for the purpose of recommending appropriate conservation and unitization statutes

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It is additionally recommended that the state immediately institute a program to acquire, compile and correlate information needed for accurate engineering studies, and to make this information readily available to all interested parties. No information relating to well production should be confidential. The very least that should be done is the enactment of a law requiring that

all gas wells be shut in for a minimum of 48 hours once a year and that shut-in pressures be recorded and reported to an appropriate state regulatory body. Open-flow capacities, or flow rates against stated back pressures, should be recorded at the time wells are shut in, and likewise reported. Though this information will not suffice for accurate computation of the wells' performance by the Bureau of Mines back-pressure method, it will provide for considerably more accurate engineering studies than are currently possible. This recommendation would be superfluous if adequate petroleum conservation laws were en-

acted, for effective conservation presupposes a requirement for accurate knowledge of both the gas reservoir and the producing wells, which can only be gained from extensive and accurate data.

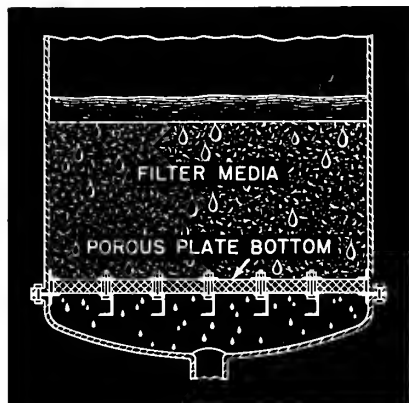
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Page

18

i

2

6

6

10

12

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10

IV. INFORMATION ON HISTORY

13

6. INFORMATION

20

a. Description of Average Well Production (Gallons per Day)

20

1. List of Wells Operating

20

2. Application of the Bureau of Land Management

21

3. Submitted to the Graduate School of the University

of Pittsburgh in partial fulfillment of the

21

4. Required course in Mining

21

requirements for the degree of

Master of Science

21

Master of Science

5. Additional Reports

21

6. Economic Aspects

21

a. General

21

b. Specific

21

VII. SUMMARY

21

VIII. REFERENCES

21

APPENDIX

21

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AN INVESTIGATION OF THE EFFECTS OF THE

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BY

CLARA BROWN GUNN

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## TABLE OF CONTENTS

	Page
FOREWORD .....	iv
I. INTRODUCTION .....	1
II. INADEQUACY OF ENGINEERING DATA .....	3
III. HISTORY OF OPERATIONS .....	6
A. The Reservoir .....	6
B. Drilling and Production Practices .....	10
1. Drilling and Casing .....	10
2. Production Practices .....	10
IV. DETERMINATION OF RESERVES .....	13
V. OPERATIONS .....	20
A. Determination of Average Well Productive Capacity ..	20
1. Bureau of Mines Equation .....	20
2. Application of the Bureau of Mines Equation ....	22
B. Effect of Well Spacing and Production Practices on Production Rate .....	25
C. Estimated Losses in Ultimate Recovery .....	27
VI. EVALUATION OF RESULTS .....	29
A. Operational Aspects .....	29
B. Economic Aspects .....	32
1. General .....	32
2. Private Landowners .....	33
VII. CONCLUSIONS AND RECOMMENDATIONS .....	34
APPENDIX I .....	37
APPENDIX II .....	43
APPENDIX III .....	49

TABLE OF CONTENTS

Page

14	FOREWORD .....
1	I. INTRODUCTION .....
3	II. IMPORTANCE OF MINING DATA .....
6	III. HISTORY OF OPERATIONS .....
6	A. The Reservoir .....
10	B. Drilling and Production Practices .....
10	1. Drilling and Logging .....
10	2. Production Practices .....
13	IV. ESTIMATION OF RESERVES .....
30	V. OPERATIONS .....
30	A. Determination of Average Well Productive Capacity .....
30	1. Bureau of Mines Equation .....
33	2. Application of the Bureau of Mines Equation .....
35	B. Effect of Well Spacing and Production Practices on Production Data .....
37	C. Estimated Reserves in Ultimate Recovery .....
39	VI. EVALUATION OF RESULTS .....
39	A. Operational Aspects .....
39	B. Economic Aspects .....
39	1. General .....
39	2. Private Investments .....
39	VII. CONCLUSIONS AND RECOMMENDATIONS .....
39	APPENDIX I .....
39	APPENDIX II .....
39	APPENDIX III .....

## TABLE OF CONTENTS (Continued)

	Page
APPENDIX IV .....	50
BIBLIOGRAPHY .....	51
gas field in Pennsylvania, and compared the results of such practices with those which might have been accomplished had the field been developed and operated in the most efficient manner.	
ILLUSTRATIONS	
Figure 1 - Structure Map, Driftwood-Benezette Gas Field .....	8
Figure 2 - Block Area Map, Driftwood-Benezette Gas Field .....	9
Figure 3 - Cumulative Production and Production Rate Versus Time .....	11
Figure 4 - Pressure Decline with Cumulative Production .....	14
Figure 5 - Pressures by Block Areas .....	17
Figure 6 - Average Well Flow-Rate Decline .....	23
Figure 7 - Compressibility Factor Versus Pressure .....	45
Figure 8 - Pressure Due to Weight of Gas Column Versus Well-Head Pressure .....	46

TABLE OF CONTENTS (Continued)

20	..... VI INDEX
21	..... VII APPENDIX

APPENDIX

8	Figure 1 - Structure map, Litchfield-Keosauqua area
9	Figure 2 - Block area map, Litchfield-Keosauqua area
11	Figure 3 - Cumulative production and production rate curves
11	Figure 4 - Pressure decline with cumulative production
13	Figure 5 - Pressure vs. block area
15	Figure 6 - Average well flow rate decline
16	Figure 7 - Comparison of block area pressure
18	Figure 8 - Pressure vs. height of the oil column



## FOREWORD

This paper presents a petroleum engineering approach to the evaluation of production practices employed in the Driftwood-Benezette gas field in Pennsylvania, and compares the results of such practices with those which might have been accomplished had the field been developed and operated in the most efficient manner, or in accordance with modern petroleum conservation laws.

The Driftwood-Benezette gas field is important to this study only in that it provides a means for illustrating production practices generally employed in all Pennsylvania gas fields. Therefore, no attempt has been made to set forth details of engineering and geologic interest not closely related to production practices.

Grateful acknowledgment is made to the engineers and geologists of the Manufacturers Light and Heat Company and the New York State Natural Gas Company for their cordial reception of the author in his quest for information and for their time and effort expended in making information available; to Professor H. G. Botset, Head of the Petroleum Engineering Department, University of Pittsburgh, and Professor P. F. Fulton, Associate Professor, Petroleum Engineering Department, University of Pittsburgh, for the suggestion of the study and for their helpful comments and recommendations; and to the U. S. Naval Postgraduate School, Monterey, California, for their sponsorship of the petroleum logistics curriculum at the University of Pittsburgh through which the author was provided with the basic opportunity for preparing this paper.

This paper presents a preliminary investigation of the

evaluation of protection procedures employed in the

gas field in Pennsylvania, and presents the results of such

those which might have been accomplished had the field been developed and

operated in the most efficient manner, in an economic sense with no

net loss of production.

The following conclusions are drawn from this study only

in that it provides a means for determining protection measures

employed in all cases, and the results of such

made to see how much of the gas field is actually

related to protection procedures.

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## I. INTRODUCTION

Petroleum production practices in Pennsylvania have remained the same in principle since the discovery of the Drake well in 1859. There are no laws restricting petroleum production even though it is a well known fact that "wide-open" flow may cause great underground losses of oil or gas; moreover, there are no laws protecting landowners' correlative rights -- the right to enjoy the use of one's property so long as this enjoyment does not do injury to others.<sup>1</sup>

There have been several proposals<sup>2</sup> for petroleum conservation laws which would require or encourage the development and operation of a petroleum reservoir as a single unit rather than on the wasteful and costly basis of "every man for himself." None has been enacted, however, and it appears that Pennsylvania may become the leading oil and gas producing state where no such laws are in effect. It is indeed a mystery why no such laws have been enacted. One would think that Pennsylvania, the founding state of the petroleum industry, would have been a leader in petroleum regulatory law. There must be some merit to petroleum conservation and unitization laws, for no state has ever repealed such a law. The Interstate Oil Compact Commission, which through engineering, research, and other committees functions to advise the various states on petroleum regulatory measures, has recommended the enactment of a unitization law.<sup>3</sup> Does it not seem logical that there should be a minimum waste of petroleum resources, and that a landowner should be permitted to recover his fair share of the oil or gas underlying his land, and only his fair share, without the drilling of unnecessary wells?

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<sup>1</sup>References are listed in the Bibliography.

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same in principle since the discovery of the first well in 1859. There

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Compact Commission, which controls interstate oil, research, and other com-

mercial practices in states the various states on petroleum regulatory

measures, has recommended the enactment of a mid-Atlantic law.<sup>3</sup> One is

not sure to find that there should be a uniform state of petroleum re-

gulation, and that a legislature should be urged not to recover this state

of 1910 or 1911 in the early 1920s, but that the state should, without

the aid of any necessary action.

Perhaps many Pennsylvanians are not acutely aware of the waste of their petroleum resources or the infringement on their correlative rights caused by maximum-rate production practices employed in Pennsylvania. This study has been made in an attempt to illustrate, quantitatively, the effects of such practices as they relate to natural-gas production.

The Driftwood-Benezette field provides a good example for illustrating natural-gas production practices in Pennsylvania. This field was intensely drilled soon after its discovery and allowed to produce at maximum rate. Each landowner had to get his gas to the surface before his neighbor drained it away. It is the author's opinion that this caused the drilling of about 200 more wells than would have been necessary to produce the field efficiently, and that open-flow production will cause the underground loss of at least 20 billion cubic feet of gas, with a net value of approximately \$2,000,000.

Unfortunately, accurate results cannot be obtained from the data available. Throughout this study, however, the author continually strove to favor the use of results and assumptions which would not exaggerate the adverse effects of existing production practices.



## II. INADEQUACY OF ENGINEERING DATA

It became apparent at the beginning of this study that the lack of petroleum regulatory laws has resulted in an inadequacy of engineering data.

It is impossible for engineers to make accurate engineering studies, upon which plans for future gas production, transportation, storage and marketing must be based, without complete and accurate engineering information. Furthermore, this information must be readily available, at a central source, to all interested parties.

In 1935 the Bureau of Mines introduced a method for computing gas-well capacities and for applying this information to production practices.<sup>4</sup> The basic equation<sup>5</sup> set forth in that report is used throughout the natural gas producing industry—even in Pennsylvania—yet the data available on Pennsylvania wells for use in that equation are entirely inadequate for accurate calculations.

Though there are no laws preventing operators from obtaining these data on their own wells, few will voluntarily close in a well or restrict its production while their neighbor drains gas from under their land at a maximum rate. Further, in order to provide maximum benefit, this information must be standardized and compiled under a well organized program, enforced by a central authority and maintained readily available at a central source.

This lack of adequate information has obviously lead to inaccuracies in much of the data that have been obtained. Probably the greatest inaccuracies have been in measuring the shut-in pressures of the wells, the very heart of the information used in petroleum engineering studies.



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Though there are no laws governing operation from obtaining these data on their own wells, the well owner usually relies on a well or operator for the production which their well produces, as from water their land is a valuable asset. However, in order to provide maximum benefit, this information must be obtained and recorded under a well's actual production collected by a central authority, and such data are readily available at a central source.

This lack of adequate information has seriously led to the occurrence of gas in some of the gas fields which have been discovered. It is the greatest danger to the gas industry in Pennsylvania, and it is the greatest danger to the gas industry in Pennsylvania, and it is the greatest danger to the gas industry in Pennsylvania.



Another source of difficulty to an engineer is the confidential nature of production information on privately owned wells. An accurate evaluation of a well's performance requires the comparison of that well with other wells in the near vicinity, and an evaluation of the reservoir as a whole may require the use of performance data on any well in the reservoir.

Specific examples of either inadequate or inaccurate information encountered during the course of this study are listed as follows:

1. Shut-in well pressures are often inaccurate. Most wells were shut in for less than 24 hours when their pressures were recorded, some for only an hour or less.
2. The entire reservoir has never been shut in and the average pressure recorded, nor are individual wells shut in periodically for this purpose. One accurate reservoir pressure, after sufficient gas had been produced to show a pressure decline, would have been sufficient to compute total gas reserves. As the situation stands, operators are merely guessing at gas reserves, and no one will ever know how much gas is lost due to production practices.
3. Production information on privately owned land is confidential and, therefore, not available to the public or to all interested producing companies.
4. No records could be found showing shut-in pressures for wells on more than one occasion after having been cut in to the pipeline. This information is necessary in order to determine a well's performance characteristics and behavior as described in Section V, A and B.
5. No one producer or regulatory body has all the data on all the wells in the reservoir. Absence of monthly production rates for all wells

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Specific examples of either inadequate or inaccurate information

encountered during the course of this study are listed as follows:

1. Spot-in well pressures are often inaccurate. Most wells were

about 10 to 15 hours when their pressures were recorded, some for only an hour or less.

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pressure recorded, nor are individual wells shut in periodically for this purpose. The accurate reservoir pressure, after sufficient gas has been

produced to show a pressure decline, would have been sufficient to compare local well reservoirs. As the official standards, operators are usually known-

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3. Production information on privately owned land is confidential

and, therefore, not available to the public or to all interested production companies.

4. To receive credit for future reserves, shut-in pressures for wells

on some land are recorded after having been out in the production. This information is necessary in order to determine a well's performance

correctly. The well has been in production for a long time, and

5. A well is not a well until it is producing. A well that is not

active in the reservoir, although it contains gas, is not a well.

is the most important example of this inadequacy. Other missing information might be as follows: The drilling method used, whether or not a well was shot, original well-head pressures and shut-in time, and whether or not a well had been abandoned.

6. The reservoir temperature has never been measured.

7. Very few reservoir sand thicknesses have been recorded.

8. Well locations are not recorded in a standard form.

9. Neither the porosity nor the permeability of the sand have ever been measured.

In view of the above, the results brought out in this study are not nearly so accurate nor significant as they otherwise might have been. Perhaps the inadequacy of this study will serve to indicate the necessity for such state statutes as will provide for the compilation of information necessary to conduct accurate engineering studies.

probably will be shown in a separate report.

It should be noted that the results of this study are not nearly as accurate as is indicated in the above report on pages 1 and 2. These errors resulted by the application of the average permeability values as reported in Section 1.

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### III. HISTORY OF OPERATIONS

#### A. The Reservoir

The Driftwood-Benezette gas field is the largest known gas field in Pennsylvania, covering about 42,000 acres in Elk, Cameron, and Clearfield counties. Production is from the highly faulted Oriskany sandstone, which in this area is mostly "medium-grained, light gray, quartzose, slightly calcareous."<sup>6</sup> The Oriskany is capped by the Onondaga limestone formation.

Figure 1 shows the approximate area of the reservoir superimposed on a contour map on the Oriskany sandstone as constructed by Fettke.<sup>7</sup> Figure 2 shows locations of all wells numbered in the sequence in which they were completed or drilling operations abandoned, although numbers for dry holes have been omitted on the drawing. Pertinent information on each producing well is shown in Appendix I.

It should not be construed that the reservoir has such a jagged boundary as is indicated by the block areas in Figures 1 and 2. These blocks established by the author were used to compute the average reservoir pressure as described in Section IV.

This field is located on the Driftwood anticline, the highest point on which is the Driftwood dome, located about one mile northeast of the town of Driftwood. This dome is not shown in Figure 1 since the dome itself proved to be outside the productive boundary of the reservoir, as indicated by the numerous dry holes shown just to the northeast of the reservoir in Figure 2.

The northeast or Driftwood end of this reservoir was discovered first. The discovery well was Sylvania's S. C. Eaton No. 1 (Figure 2,

The first question presented is whether the evidence in this case is sufficient to establish that the defendant is guilty of the crime charged. The evidence in this case is circumstantial, and the question is whether it is sufficient to establish the defendant's guilt beyond a reasonable doubt. The evidence in this case is circumstantial, and the question is whether it is sufficient to establish the defendant's guilt beyond a reasonable doubt.

Figure 1 shows the approximate size of the defendant's apartment on a compass map of the city. The apartment is located in the center of the city, and the map shows the surrounding streets and landmarks. The apartment is located in the center of the city, and the map shows the surrounding streets and landmarks.

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well 1-A) completed September 15, 1951. Since this well was situated relatively low on the southwest plunge of the Driftwood dome, subsequent tests were made high on the dome in and around the town of Driftwood, none of which proved productive apparently because of a tight sand stratigraphic closure at the northeast end of the reservoir. Development was then shifted down the plunge to the southwest.

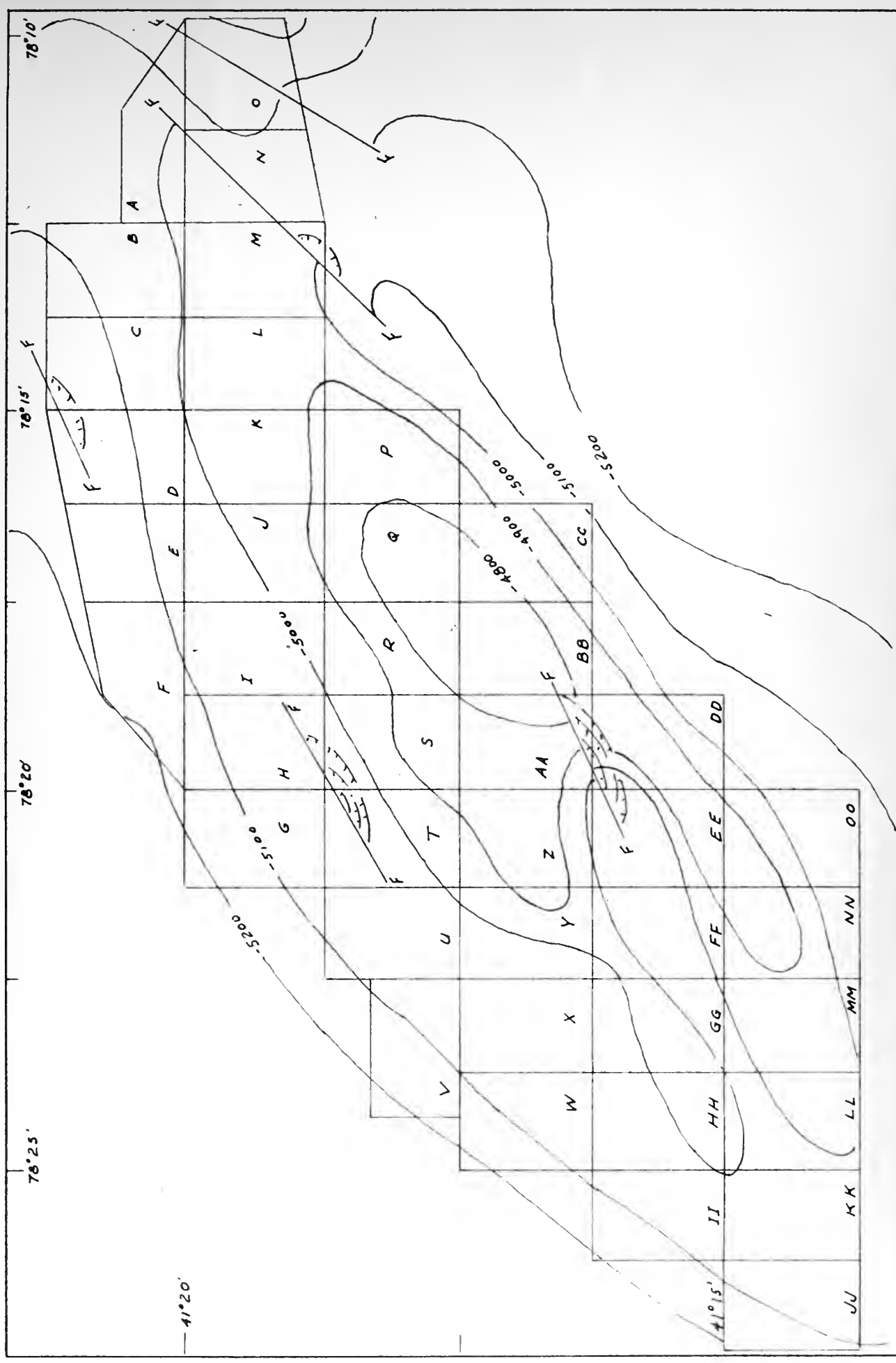
The Keta Oil and Gas Company's Charleroi Mountain Club No. 1 (Figure 2, well 57-S) on the Benzette dome opened the Benzette end of the reservoir in December, 1952. Then in March, 1953, the Benzette Valley Development Company brought in the William Woodring No. 1. (Figure 2, well 69-F) This well was extremely important in that it is some 300 feet lower on the flanks of the Benzette dome than the Charleroi well, indicating that the Driftwood-Benzette field was much larger than had previously been estimated.<sup>8</sup> This led to the furious drilling race between private landowners which resulted in the dense well pattern as shown in Figure 2, areas F, G and H. Presumably, if the areas to the south had not been mostly state-owned land, the entire field would have been drilled into a similar pattern.



well 1-4) completed September 12, 1921. Since this well was situated relatively low on the southeast slope of the Hillwood dome, independent tests were made high on the dome in and around the town of Hillwood, some of which proved productive apparently because of a tight sand stratum. Graphs obtained at the northeast end of the reservoir. Development was then shifted down the slope to the southeast.

The Hill and Lee Company's Standard Mountain Club No. 1 (Figure 5, well 2-5) on the northeast dome opened the reservoir end of the reservoir in December, 1925. Then in March, 1926, the Hillwood Valley Development Company brought in the William Woodring No. 1 (Figure 5, well 3-7). This well was extremely important in that it is some 300 feet lower on the flanks of the northeast dome than the Hillwood well, indicating that the Hillwood-Standard field was much larger than had previously been estimated.<sup>6</sup> This led to the further drilling now between private landowners which resulted in the three wells shown in Figure 5, areas 1, 2 and 3. Presumably, if the areas to the south had not been mostly steam-heated land, the entire field would have been drilled into a similar pattern.





Contours on Oriskany Sandstone  
Figure 1 Structure Map Driftwood-Benezette Gas Field



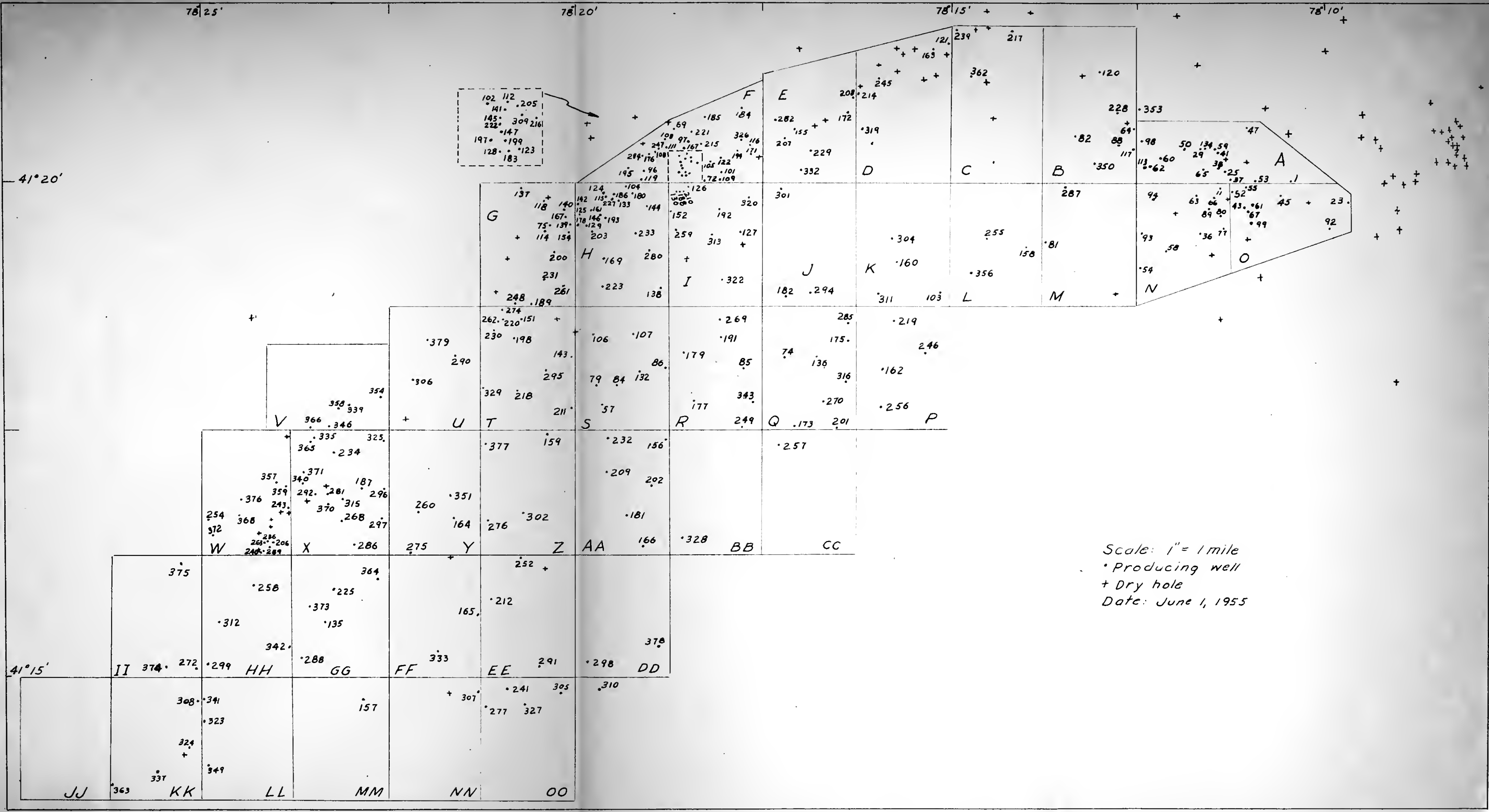


Figure 2. Block Area Map, Driftwood-Benezette Gas Field



## B. Drilling and Production Practices

### 1. Drilling and Logging

Drilling operations reached a peak in August, 1953 when 22 producing wells were brought in. The rate then dropped slightly and leveled off at about fifteen to twenty wells per month until July, 1954, at which time there began a rapid decline in the drilling rate. Appendix IV shows a detailed breakdown of the wells by months.

Most of the early drilling was with cable tools which averaged about sixty feet per day. Rotary drilling was later used, which averaged about 180 feet per day; however, lost circulation and completion problems were frequently caused by the high density (17 pounds per gallon) drilling mud. Completion problems were often overcome by drilling-in with cable tools, but a more recent practice of using air-rotary drilling with gas completions has been highly successful in eliminating both of these difficulties. The air-rotary has shown a penetration rate of about twice that of the regular rotary.<sup>9</sup>

All methods employ the practice of setting a seven-inch O. D. casing about ten feet into the Onondaga limestone, and then drilling a 6 1/8 inch hole into or through the Oriskany sandstone.

Open-flow capacities of wells are measured with pitot tubes while the gas is discharged to the atmosphere. Shut-in pressures are generally recorded after wells have been closed in for 24 hours, although the rush to cut the wells into the pipeline frequently permits only a few hours shut-in time.

### 2. Production Practices

Little can be said of production practices except that wells are cut in to the pipeline as quickly as possible and permitted to flow at

## B. Drilling and Production Practices

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All wells are cased to the bottom of the hole and are cemented. The casing is usually 10 inches in diameter and is cemented with 1500 psi concrete.

Flow-line connections of wells are completed with 1/2 inch tubing. The tubing is usually 10 inches in diameter and is cemented with 1500 psi concrete. The tubing is usually 10 inches in diameter and is cemented with 1500 psi concrete.

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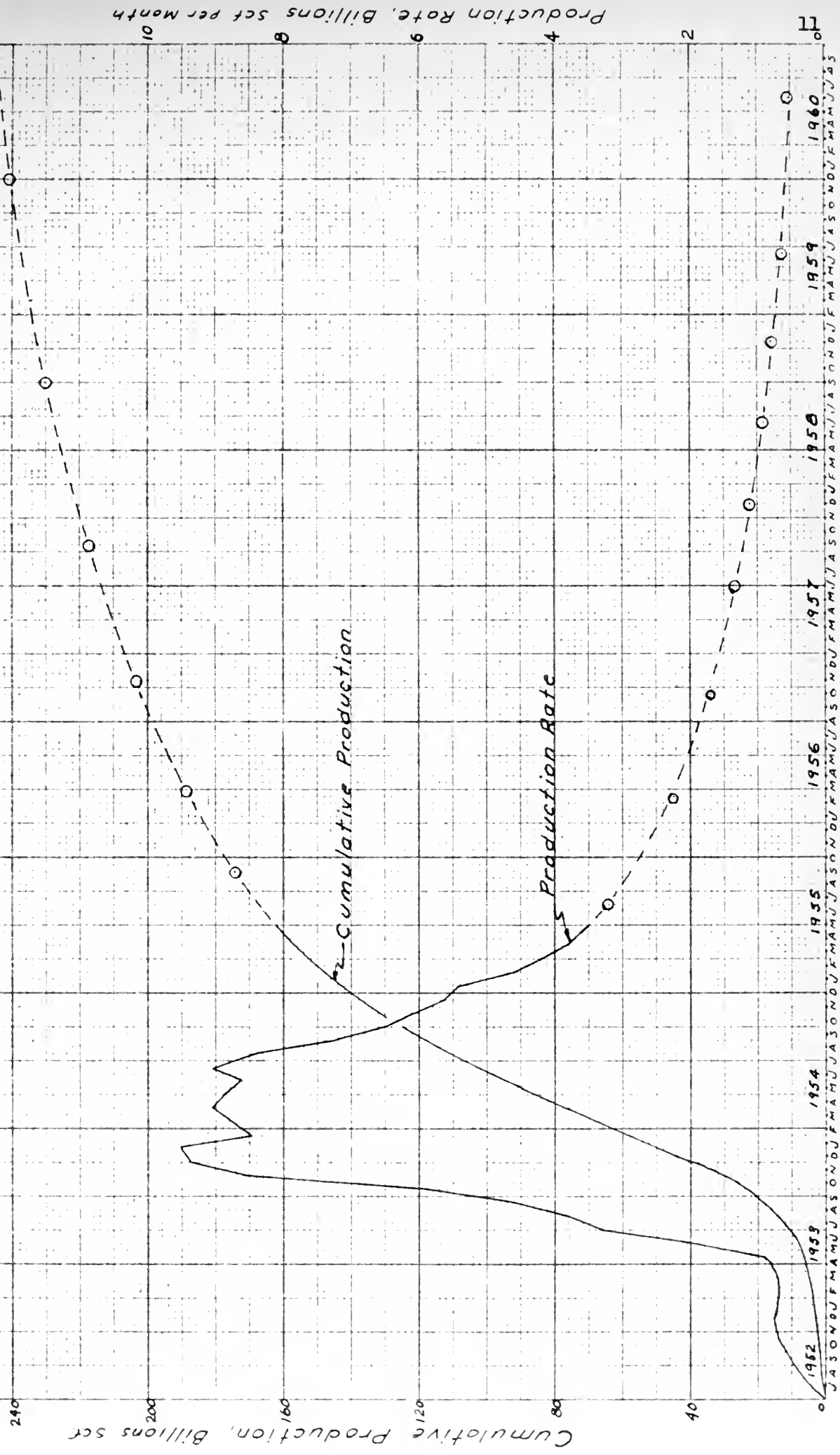


Figure 3. Cumulative Production & Production Rate vs. Time  
Months Ending





maximum rate. Figure 3 shows the cumulative production and production rate of the field plotted against time. The dotted portion of the curves represents the predicted recovery and recovery rates as explained in detail in Section V, C. Actual production figures are shown in Appendix III.

There has been no evidence of water drive during production from this field. There have been occasions of wells being drowned out by water, but this difficulty has frequently been relieved, at least temporarily or partially, by shutting in the wells for a few days.

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## IV. DETERMINATION OF RESERVES

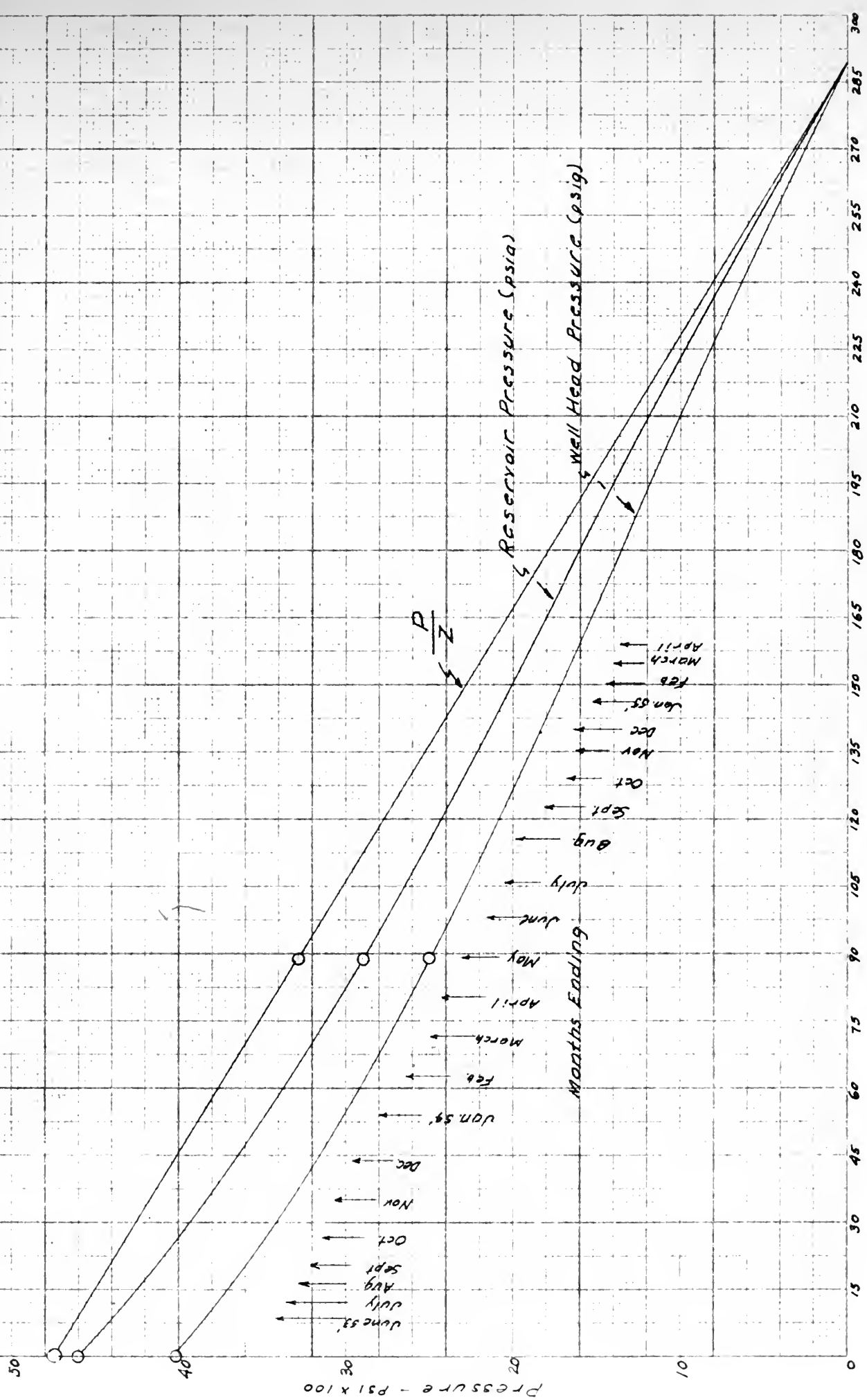
An accurate determination of gas reserves in a reservoir can be made only when accurate reservoir pressures are known. Since the Driftwood-Benezette reservoir has never been shut in, in order to determine a reservoir pressure, and since pressures for individual wells are not periodically recorded, any method used in computing reserves is largely guesswork. The original reservoir pressure was most probably about 4020 pounds per square inch gage, as measured at the well head. Obviously, no other pressure would be needed to compute reserves if the boundaries of the reservoir, the porosity, the per cent water saturation, and the sand thickness were known. However, in view of the highly faulted structure of this reservoir, the probable wide variation in porosity, and the doubtful boundaries as estimated, the only practicable method for determining reserves is by the use of declining reservoir pressures with cumulative production, as is shown graphically by Figure 4, and as explained in detail later in this section.

The only course for determining the average reservoir pressure lay in averaging pressures by areas, area pressures being obtainable from original pressures for new wells as shown in Appendix I. It is believed that the boundaries of the reservoir are sufficiently well established so that it can be divided into areas as shown in Figure 2, and that each area has roughly the same average porosity and sand thickness. Though this may not be entirely true, the method of averaging area pressures in order to determine the over-all reservoir pressure is not overly demanding of an accurate reservoir area, and it is not necessary that the sand thickness or porosity be known, provided each area is assumed to have equal pore

#### IV. ESTIMATION OF RESERVES

An accurate determination of the reserves in a reservoir can be made only when accurate reservoir pressure data are known. Since the difference between reservoir pressure and atmospheric pressure is not negligible, and since pressures for individual wells are not readily easily measured, the method used in computing reserves is fairly approximate. The original reservoir pressure was most probably about 1000 pounds per square inch (psi), as indicated by the well heads. Obviously, no other pressure would be needed to compute reserves if the boundaries of the reservoir, the porosity, the permeability, the porosity, and the sand thickness were known. However, in view of the highly faulted character of this reservoir, the probable shape variation in porosity, and the doubtful boundaries as estimated, the only practical method for determining reserves is by the use of declining reservoir pressure with cumulative production, as is shown graphically by Figure 1, and as explained in the text later in this section.

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Cumulative Production - Billions scf

Figure 4. Pressure Decline with Cumulative Production



space. The reservoir area as shown is comprised of forty-one approximately equal-sized blocks of about one thousand acres each.

The only difficulty lay in determining the average area pressures at a selected date or dates. The pressure recorded for a well drilled in the area on or near the selected date could not be used with any degree of accuracy, for often the well would be in such close proximity to another that its pressure would be greatly affected, or the pressure shown for a well drilled at a later date in the same vicinity might have been considerably higher. Many additional factors had to be considered, such as the location of the wells in the area, their distance apart, the length of shut-in time compared to flow rate, and pressures in adjoining areas.

It soon became apparent that many recorded well pressures were lower than they should have been. Most of the wells were shut in for less than twenty-four hours when their pressures were recorded. This is far short of the time estimated to have been necessary for the pressure to stabilize in sand of such low permeability. It has been illustrated that pressures recorded after three days may still be well below the stabilized pressures.<sup>10</sup>

It was impossible to select any single date near which, during the early and late stages of development, wells were drilled in a majority of the areas. This required such an extensive use of estimated area pressures that little reliability could be placed in the computed average. It was, therefore, decided to determine the one most accurate average reservoir pressure which occurred well along in the productive life of the reservoir. Only one pressure, other than the original, is needed to compute reserves, and one good pressure is considered to be more accurate than a decline curve average of several poor ones. In order to determine

space. The reservoir with its cover is composed of forty-one segments.

Each segment is about one thousand square feet.

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that the pressure would be greatly affected, or the pressure would be

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the location of the well in the area, the distance from the well to the

area in the company of the well, and pressure in adjacent areas.

It was found that the pressure in the well was not the same

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the most accurate pressure each block area was considered separately. Again, weighing all significant factors stated above, every instance in which a well pressure or several well pressures appeared to reasonably represent that for the block area was recorded under the date shown. When such pressures for all areas had been recorded, the widest coverage of area pressures fell near the date of May 31, 1954. That date was, therefore, selected for determining the over-all average reservoir pressure. In cases where a block area failed to show a pressure on or near that date, it was possible to interpolate between dates on either side of May, 1954 or to estimate the area pressure from those shown for surrounding areas. Well-head pressures thus determined are shown in Figure 5. The average of these gage pressures came to 2490 pounds per square inch.

The pressure due to the weight of the column of gas was computed as shown in Appendix II, using the equation

$$P_w = \frac{P_x ZRT M}{H} - .5P_x^*$$

where  $P_w$  = well head pressure in pounds per square inch absolute,

$P_x$  = pressure due to the weight of the gas column in pounds per square inch,

$Z$  = gas compressibility factor at average temperature in the well bore and at well head pressure,

$R$  = gas constant,

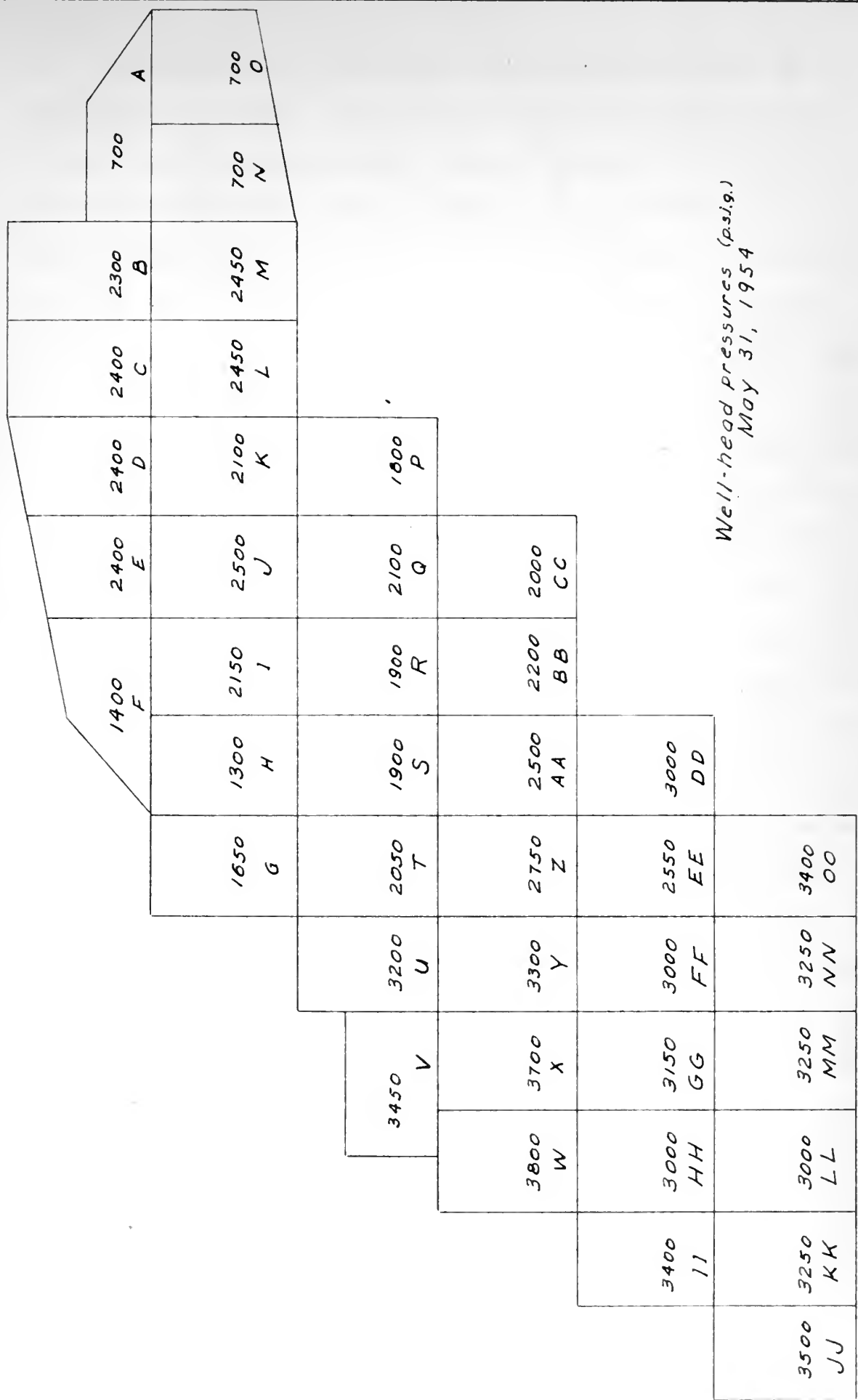
$T$  = average temperature of the gas column,

$M$  = molecular weight of the gas,

$H$  = average depth of the reservoir below the surface.

\*Derived, using gas law equations, slightly inaccurate as the  $Z$  is based on the well head pressure instead of the average pressure in the well.





Well-head pressures (psig.)  
May 31, 1954

Figure 5. Pressures by Block Areas



If natural gas expanded upon release in pressure exactly in accordance with Boyle's law, the pressure decline curve would merely be a straight line through the original reservoir pressure and the May 31, 1954 reservoir pressure plotted against cumulative production as of May 31, 1954. However, since natural gas does not conform exactly to Boyle's law, the compressibility factor had to be considered. Calhoun shows that reservoir pressure (P) divided by the compressibility factor for the gas (Z) at reservoir conditions will plot as a straight line against cumulative production.<sup>11</sup> Compressibility factors were, therefore, computed for the two above reservoir pressures as shown in Appendix II and a straight line plot made between the two P/Z points thus determined. The accuracy of the curve was checked analytically, also as shown in Appendix II. The reservoir pressures as they would be measured both in the reservoir and at the surface (Figure 4) were computed from the P/Z curve, using compressibility factors and values for the pressure due to the weight of the gas column as are shown graphically in Figures 7 and 8, Appendix II.

The 239 billion standard cubic feet of gas, as calculated to have been originally in the reservoir, at first appeared high, considering the present low production rate from the wells. An additional calculation was, therefore, made to determine the porosity of the sand, using 42,000 acres which has been estimated as the area of the reservoir, and an average sand thickness of 17 feet as estimated from the few well records showing this information. The porosity thus calculated, as shown in Appendix II came to 4.18 per cent. This porosity certainly does not appear to be excessive, considering the nine per cent and 8.34 per cent porosities found, respectively, for Oriskany sand samples blown from wells in the Tioga<sup>12</sup> and the Leidy gas fields.<sup>13</sup>

[illegible]

In consideration of the above, the 289 billion cubic feet does not appear to be excessive. An additional similar calculation of reserves was made, however, using the absolute minimum feasible pressures for block areas as of May 31, 1954. This calculation showed 255 billion standard cubic feet as the original gas content of the reservoir. The original calculation is considered to be the more accurate.

The following is a summary of the data used in the calculation of the original gas content of the reservoir. The data are based on the results of the interpretation of the seismic data and the results of the drilling and production data. The data are summarized in the following table:

$$G = \frac{V_p \cdot \Delta \rho \cdot \Delta z}{\Delta \rho \cdot \Delta z}$$

where  $G$  = gas content of the reservoir, in standard cubic feet

$V_p$  = pore volume of the reservoir

$\Delta \rho$  = difference in density between the gas and the liquid

$\Delta z$  = thickness of the reservoir, in feet

The following is a summary of the data used in the calculation of the original gas content of the reservoir.

The data are based on the results of the interpretation of the seismic data and the results of the drilling and production data. The data are summarized in the following table:

The following is a summary of the data used in the calculation of the original gas content of the reservoir. The data are based on the results of the interpretation of the seismic data and the results of the drilling and production data. The data are summarized in the following table:

In consideration of the above, the 252 million cubic feet does not appear to be excessive. An additional similar calculation of reserves was made, however, using the average minimum possible pressure for block cross as of May 31, 1934. This calculation showed 252 million standard cubic feet as the original gas content of the reservoir. The original oil-oilation is considered to be the same amount.



## V. OPERATIONS

### A. Determination of Average Well Productive Capacity

#### 1. Bureau of Mines Equation

The Bureau of Mines has reported<sup>14</sup> that:

"For normal gas wells there is a consistent relationship between rates of delivery of gas and corresponding pressures when the pressures in the sand are used as the basis for interpretation. Results of tests throughout the United States show that when the rates of delivery are plotted on logarithmic paper against  $(P_f^2 - P_s^2)$  - the respective differences of the squares of the formation pressure,  $P_f$ , and the pressure at the sand face,  $P_s$  - the relationship is represented by a straight line, which may be expressed mathematically by the formula

$$Q = C(P_f^2 - P_s^2)^n$$

where  $Q$  = rate of flow, M cubic feet per 24 hours,

$C$  = coefficient,

$P_f$  = "shut-in" formation pressure, pounds per square inch absolute,

$n$  = exponent, corresponding to the slope of the straight line relationship between  $Q$  and  $(P_f^2 - P_s^2)$  plotted on logarithmic paper."

It is further pointed out in that report<sup>15</sup> that the value of  $n$ , or the slope of the logarithmic plot, would remain constant if no physical changes occurred in the well bore or in the producing formation which affected the productive capacity of the well.

This Bureau of Mines report recommends the above relationship as a means for analyzing the deliverability of gas wells. The procedure involves, essentially, the periodic shutting in of the well to determine the formation pressure ( $P_f$ ), and then permitting the well to flow at decreasing back pressures ( $P_s$ ) during which time the rate of flow ( $Q$ ) is measured

Information to be furnished to the President

1. Summary of the situation

2. Details of the situation

3. Recommendations for action

$$x^2 + y^2 = z^2$$

4. Summary of the situation

5. Details of the situation

6. Recommendations for action

7. Summary of the situation

8. Details of the situation

9. Recommendations for action

10. Summary of the situation

11. Details of the situation

12. Recommendations for action

13. Summary of the situation

14. Details of the situation

15. Recommendations for action

16. Summary of the situation

for each back pressure. The logarithmic plot described above can be extrapolated to determine the open flow capacity of the well without the necessity of venting the well to the atmosphere and thereby wasting gas and probably damaging the well.<sup>16</sup> When flow rates so determined at periodic intervals fail to fall on the same straight-line logarithmic plot, it is indicative of changes occurring in the well or the producing formation, such as water coning, water condensation, well caving, etc. This procedure also provides a means for predicting flow rates at various back pressures and formation pressures, and for analyzing the effects of measures taken to increase a well's productive capacity.

A Bureau of Mines report<sup>17</sup> some nine years later carried an interesting discussion of the value of  $n$  as related to a similar exponent in an equation<sup>18</sup> for isothermal flow derived and confirmed experimentally by Muskat and Botoet, where the latter had shown, in effect, that the value of  $n$  in the equation  $Q = C(P_f^2 - P_g^2)^n$  would range from 0.5 for wholly turbulent flow to 1.0 for wholly viscous flow. The Bureau of Mines report stated that it had been shown experimentally that the value of  $n$  ranged from 0.6 to 1.2 and that there was no significant bending of the logarithmic plot toward the pressure axis for increased values of  $(P_f^2 - P_g^2)$  and  $Q$ , as might have been expected.

It is significant to note, however, that the second Bureau of Mines report was based largely on results of tests set forth in the first report and that both field and experimental results<sup>19</sup> were obtained from highly permeable sands through which gas was flowing under relatively low pressures. It is further significant to note that many laboratory tests did show logarithmic plots that bent slightly toward the pressure axis with increasing values of  $Q$  and  $(P_f^2 - P_g^2)$ , and that there appears to be



no confirmation in laboratory tests for values of  $n$  greater than one. One might, therefore, surmise that possibly there could be a significant bending of the logarithmic curve toward the pressure axis with greatly increasing values of  $(P_f^2 - P_g^2)$  and  $Q$  and that possibly the few cases during field tests where the value of  $n$  exceeded one resulted from physical changes occurring in the well bore or from inaccurate data. It is the author's opinion that values of  $n$  greater than one should be accepted with reservations, if at all.

## 2. Application of the Bureau of Mines Equation

The equation  $Q = C(P_f^2 - P_g^2)^n$  as previously described is also applicable to groups of wells.<sup>20</sup> The average well productive capacity coefficient  $C$ , may therefore be obtained by averaging the  $C$ 's computed for each well by dividing  $Q$  by  $(P_f^2 - P_g^2)^n$ . Values for  $Q$  and for  $P_f$  as measured at the well head are shown in Appendix I. Since the value of  $n$  was not known, it was necessary to average the production rates ( $Q$ ) for wells producing under the same  $(P_f^2 - P_g^2)$ . Further, since little confidence could be placed in the accuracy of the lower pressures, it was decided to use wells showing well-head pressures near 3500 pounds per square inch. Thirty such wells showed an average  $Q$  of 7300 M cubic feet per day. The pressure due to the weight of the column of gas in these wells averaged about 500 pounds per square inch, bringing the  $P_f$  value to 4000 pounds per square inch. Since  $P_g$  can be neglected for these large-hole high-pressure wells flowing against atmospheric pressure, 7300 ( $Q$ ) can be plotted against 16,000,000 ( $P_f^2 - P_g^2$ ) on logarithmic paper as is shown by point A in Figure 6. This gives one point on the logarithmic plot, but does not of course show the slope of the line which can be used to determine values of  $Q$  at different values of  $(P_f^2 - P_g^2)$ . It was decided to use an  $n$  value of one (viscous flow) in order to simplify calculations and to preclude the exaggeration

no correlation in laboratory tests for values of  $\alpha$  greater than one. The  
 right, therefore, indicates that possibly there would be a significant  
 lag of the logarithmic curve from the present rate of growth in-  
 creasing value of  $(\frac{1}{2} - \frac{1}{2})$  and  $\alpha$  and that possibly the two cases being  
 listed were shown the same of a number one revealed from physical  
 changes occurring in the well bore or from formation water. It is the  
 author's opinion that values of  $\alpha$  greater than one should be accepted with  
 reservations, if at all.

3. Application of the theory of linear regression  
 The equation  $y = a + b(x - \bar{x})$  is previously mentioned in this appli-  
 cation to the case of wells. The average well production is usually  
 classed as low production or average production. The  $\bar{x}$  is computed for each  
 well by dividing  $y$  by  $(\frac{1}{2} - \frac{1}{2})$ . Values for  $\bar{x}$  and for  $\bar{y}$  are computed as  
 the well head are shown in Appendix I. When the value of  $\alpha$  is not known,  
 it is necessary to average the production rates ( $\bar{y}$ ) for wells producing  
 under the same  $(\frac{1}{2} - \frac{1}{2})$ . Further, when little confidence could be placed  
 in the accuracy of the lower production, it was decided to use wells which  
 are well-known producers near 3000 barrels per square foot. The  $\bar{y}$  and  
 wells shown an average of 17.5 barrels per day. The pressure was  
 to the right of the column of the  $\bar{y}$  value wells averaged about 200 barrels  
 per square foot, indicating the  $\bar{y}$  value to 4000 barrels per square foot.  
 Since  $\bar{y}$  can be neglected for these logarithmic regression wells showing  
 a linear relationship between  $\bar{y}$  and  $\bar{x}$  and no plotted values is 10,000,000  
 $(\frac{1}{2} - \frac{1}{2})$  on logarithmic paper as is shown by Figure 4 in Appendix I. This  
 shows the point on the logarithmic paper, and also the value of  $\bar{y}$  shown the  
 above in the same column and also the value of  $\bar{x}$  on logarithmic  
 paper as shown in Appendix I. The value of  $\bar{y}$  is 10,000,000  
 and the value of  $\bar{x}$  is 10,000,000.



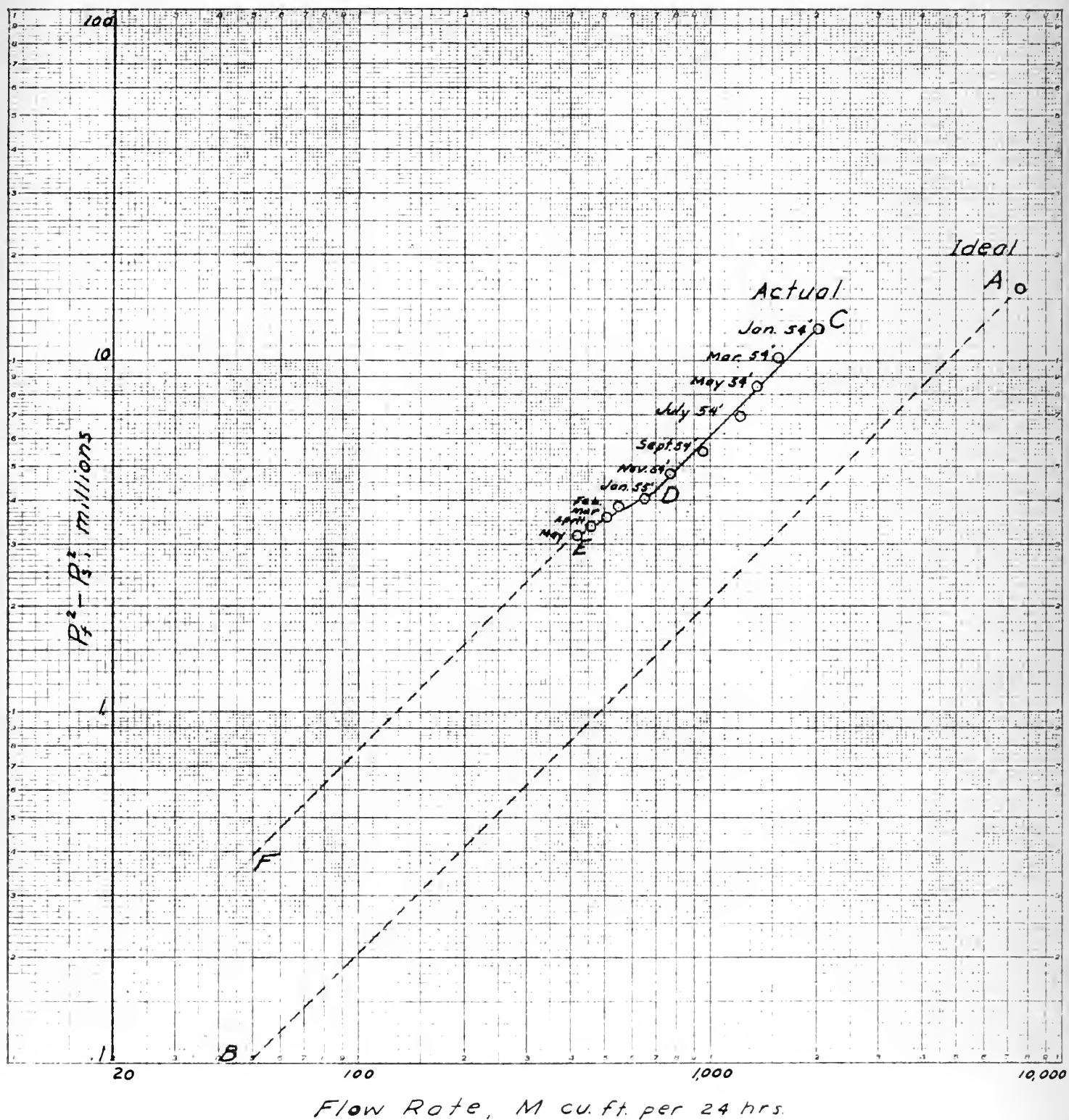


Figure 6. Average Well Flow Rate Decline





of the adverse effects of production practices as is brought out in Section V, B and C. Using this  $n$  value of one, the coefficient ( $C$ ) for the 30 wells came to .456. These values of  $C$  and  $n$  were justified by an average value of  $C$  equal to .45 for 127 wells on which the recorded data appeared to be the most accurate. The value of  $C$  for each individual well in this case was obtained by dividing the flow rate ( $Q$ ) by  $(P_f^2 - P_g^2)$ ,  $P_f$  being the closed-in individual well-head pressure plus the pressure caused by the weight of the gas column, and  $P_g$  again neglected.

Readers might be interested in the calculation of average permeability as shown in Appendix II where the value of  $C$  equal to .456 was substituted in the Darcy's law radial flow equation for viscous flow. Though a rough assumption had to be made for the drainage radius and though the flow may not be considered as radial in all cases, the computed permeability of 4.05 millidarcies as compared to the estimated permeability of ten millidarcies tends to substantiate the assumption that the value of  $C$  is not excessive. Two samples blown from wells in the Loidy gas field averaged 10.9 millidarcies.<sup>21</sup>

In consideration of the above, the curve AB in Figure 6 may be considered to represent the production rate that could have been expected from the average well with decreasing values of  $(P_f^2 - P_g^2)$  had the physical characteristics of the well and the producing formation remained constant, and had the wells been so spaced as to have the average formation pressure acting on each well.

of the various effects of production processes as in providing out in  
 Section 7, 8 and 9. Using this a value of one, the coefficient (2) for  
 the 30 wells came to 1.425. These values of 0 and 1 were justified by an  
 average value of 0 equal to 0.5 for 177 wells in which the recorded data  
 appeared to be the most accurate. The value of 0 for each individual well  
 in this case was obtained by dividing the flow rate (Q) by  $(P_1^2 - P_2^2) \cdot L$   
 being the observed-inflow well-head pressure minus the pressure constant  
 by the weight of the gas column, and  $L$  again neglected.  
 Results might be interpreted in the calculation of average perme-  
 ability as shown in Appendix II where the value of 1 would be 1.425 and the  
 obtained in the average flow rate from equation for average flow. Though  
 a rough assumption but to be made for the drainage radius and through the  
 flow may not be considered as valid in all cases, the constant perme-  
 ability of 0.05 millidarcies as compared to the estimated permeability of 0.1  
 and 0.15 millidarcies seems to substantiate the assumption that the value of  
 0 is not erroneous. The average flow from wells in the study was 1400  
 averaged 10.4 millidarcies.

In a comparison of the above, the value of 0.1 may be  
 considered as representing the production rate that would have been expected  
 from the average well in a reservoir having a value of  $(P_1^2 - P_2^2) \cdot L$  and the highest  
 permeability of the well and the producing formation remained constant.  
 and the value of 0.1 may be considered as having the average formation permeability  
 applied to each well.

## B. Effect of Well Spacing and Production

### Practices on Production Rate

As pointed out in the previous section, curve AB (Figure 6) represents the declining production rates with declining  $(P_f^2 - P_g^2)$  values that could have been expected from average, undamaged, properly spaced wells. Curve CD (Figure 6) represents the actual average production rate per well with declining average reservoir pressures as shown in Figure 4. Points on curve CD were determined by dividing the total monthly production rates (Appendix III) by the average number of producing wells as of the date indicated (Appendix IV) and plotting these rates per well against the  $(P_f^2 - P_g^2)$ ,  $P_f$  being considered as the formation pressure shown by Figure 4 and  $P_g$  being estimated as 600 pounds per square inch. The deficiency in production rate per well for any value of  $(P_f^2 - P_g^2)$  is represented by the horizontal distance between the two curves. This loss can be attributed to local pressure depletions in densely drilled areas and to physical damage to wells brought on by the rapid production rate.

Losses in production rate resulting from dense well spacing and consequent local pressure depletions can be well illustrated by considering areas F, G, and H in Figure 2, where on May 31, 1954 some 73 wells were producing under a formation pressure of about 1700 pounds per square inch. If the back pressure at the sand face was 600 pounds per square inch, the production rate per well expressed as a per cent of the production rate which would have been attained under the average reservoir pressure of 2895 pounds per square inch at that time was

$$\frac{(1700^2 - 600^2)(100)}{(2895^2 - 600^2)} = 31.5 \text{ per cent}$$

Actually the formation pressure acting on many of the wells was probably considerably less than the average for the area. It is therefore obvious



that a well drilled in this area at that time produced gas at less than one-third the rate that could have been expected of it had unit operation been in effect, or that the same total production rate for this area could have been achieved with less than one-third of the wells.

Production losses caused by water coning, well caving, etc., cannot be well illustrated from the data available, although it would be a simple procedure to shut in wells occasionally and to plot the  $Q$  versus the  $(P_f^2 - P_s^2)$  on logarithmic paper. A line through successive points thus obtained would indicate whether or not a well is being damaged. A curve that bent toward the pressure axis would be indicative of water coning or other factors hindering deliverability. If only two points are available, and a line through the two points has a slope greater than one (more than 45 degrees to the pressure axis), it will, in the author's opinion, be a positive indication of well damage. This procedure was attempted for the few state wells on which records could be found showing shut-in pressures sometime after their original gaging. However, curves thus obtained only served to prove the inadequacy and inaccuracy of recorded data. One curve showed a reverse slope, indicating lower flow rate with increasing formation pressure.

The Bureau of Mines back-pressure method for analyzing the deliverability of gas wells, as described briefly in Section V, A is a much more thorough and detailed procedure than that described above. Far greater benefits than that discussed above may also be derived from their method, although it requires the restricting of a well's flow for considerably more time than production practices in Pennsylvania permit.

[illegible]



### C. Estimated Losses in Ultimate Recovery

Although it is impossible to predict the ultimate gas recovery from this reservoir with any degree of accuracy, it is fairly obvious in view of the declining production rate that an uneconomical production rate will be reached long before 239 billion cubic feet of gas have been produced.

Curve DE, Figure 6, shows a recent increasing rate of decline in production rate. This may be due to a variety of factors, such as

1. Water fingering cutting off relatively high pressure gas zones.
2. Water coning near the well bore, reducing the effective sand thickness.
3. Water condensation, reducing the effective permeability to the gas.
4. Well caving
5. Structural conditions within the reservoir.
6. The temporary shutting in of an increasing number of wells (since the rate is based on the number of producing wells as drilled rather than the actual number in operation).
7. Almost total pressure depletion in densely drilled areas.

It is the author's opinion, however, that conditions in the reservoir may soon stabilize and that the flow rate after that time will continue in a directly proportional relationship with  $(P_f^2 - P_s^2)$ ; at least this is the best that can be expected. This is illustrated by the curve EF, Figure 6. Though there is little chance that this curve will hold true to the abandonment date, it is not unreasonable to expect that it will hold approximately true for the next few years. This curve may be used in conjunction with the reservoir pressure curve (Figure 4) to

# Oil Reserves in the United States

Although it is impossible to predict the ultimate oil recovery from this reservoir with any degree of accuracy, it is fairly obvious in view of the declining production rate that an accelerated production rate will be reached long before 1980 billion cubic feet of oil have been produced.

Curve 2, Figure 2, shows a constant increasing rate of decline in production rate. This may be due to a variety of factors, such as

1. Water flooding causing oil relatively high pressure.
2. As oil coming from the well head, reducing the effective sand thickness.
3. Water contamination, reducing the effective permeability of the sand.
4. Well clogging.
5. Structural conditions within the reservoir.
6. The reservoir shutting in at an increasing number of wells (since the rate is based on the number of producing wells as divided rather than the actual number in operation).

7. Almost total pressure depletion in heavily drilled areas.

It is the author's opinion, however, that conditions in the reservoir may soon stabilize and that the flow rate after that time will conform to a slightly hyperbolic relationship with  $(t/t_0)^{-1/2}$  at least this in the last that can be expected. This is illustrated by the curve 3, Figure 2. It is obvious that this curve will hold true to the abandonment date, it is not unreasonable to expect that it will not significantly vary in the next few years. This curve will be used to estimate the ultimate oil recovery from this reservoir.



provide a trial and error means for predicting future production and production rates. The dotted portions of the curves (Figure 3) were derived in this manner, considering a gradually decreasing value of  $P_g$  to zero in the year 1959. By the end of the year 1959 there should have been about 240 billion cubic feet of gas produced from this reservoir.

In consideration of curves AB and EF (Figure 6) and assuming a minimum economic flow rate ( $Q$ ) of 50 MCF per day at zero back pressure ( $P_g$ ), the reservoir could be expected to be abandoned at an average pressure ( $P_f$ ) of 632 pounds per square inch, whereas in the "ideal" case the abandonment pressure would be 316 pounds per square inch. This, according to Figure 4, reflects a loss of about 22 billion cubic feet of gas due to inefficient production practices.

Actually, it is anyone's guess as to just how far into the future this reservoir will produce gas at an economic rate. Most likely there will be numerous wells capable of producing gas at an economic rate for many years to come. It is highly probable, however, that water fingering and coning has or will cut off relatively high pressure zones within the reservoir, and that a reduced effective permeability to gas caused by water coning and condensation will seriously curtail production and reduce the ultimate recovery. An estimated loss of approximately 20 billion cubic feet of gas is considered to be conservative.

provide a trial and error means for predicting future production and  
 production rates. The total portion of the curve (Figure 1) was de-  
 rived in this manner, constituting a "reduced effective" value of 2.5 to  
 rate in the year 1975. At the end of the year 1975 there should have  
 been about 120 billion units left of the production from this inventory.  
 In consideration of curves A and B (Figure 2) and assuming a  
 constant economic time rate (Q) of 50 per cent as were these curves

(Figure 3). The inventory will be expected to be exhausted at an average  
 pressure (P) of 0.5 units per square inch, constant in the "ideal" case  
 the corresponding pressure would be 1.5 units per square inch. This, con-  
 sidering to 17 units of volume a loss of about 25 billion units when it  
 can be so effectively produced.

Consequently, it is expected that it will have been lost into the future  
 this inventory will produce 250 as an economic rate. Most likely there  
 will be decrease with respect to producing 250 as an economic rate for  
 many years to come. It is highly probable, however, that after 1975  
 and coming out of this will not only help pressure rates within  
 the reservoir, but that a reduced effective permeability to gas caused by  
 water content, and permeability will eventually control production and reserve  
 the ultimate recovery. An estimated loss of approximately 30 billion  
 cubic feet of gas is expected to be conservative.

## VI. EVALUATION OF RESULTS

### A. Operational Aspects

Although this study has developed no absolute proof that there will be substantial losses in ultimate recovery of gas from this reservoir, it does indicate that such losses are very likely and presents definite proof that a great amount of manpower and materials have been unnecessarily expended. Curves AB and CD (Figure 6) show that actual production per well was only about 35 per cent of what might have been expected from the properly-spaced average well, or that about one-third of the wells, if properly spaced and undamaged, should have given the same production rate. As was pointed out in Section V, A, 2, this figure is based on a conservative estimate of the slope of the logarithmic curve AB (Figure 6) equal to one. It is possible that this curve could have had a slope of less than one, showing an increasingly wide separation between the "ideal" and "actual" curves with decreasing pressures, and therefore an increasingly poorer comparison of the actual well production rate with that of the ideal.

The ideal number of wells can only be determined by an economic balance of a great many factors, such as recoverable gas in place, drilling costs, back pressure required to prevent damaging the well or the producing formation, market demands and commitments and others. The back pressure required can be determined accurately by the Bureau of Mines method, but even this is subject to economic considerations. It may, for example, be more economical to permit minor damage to the well than to hold the back pressure sufficiently high to prevent damage entirely. Some states force the application of back pressure by restricting gas

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production to 25 per cent of open flow capacity. However, this restriction is also intended to prevent gas production in excess of market demands, and there is no reason known to the author why Pennsylvania should restrict production to this rate if it can be shown that significant damage will not occur to wells producing at higher capacities. All of the above factors can best be weighed and applied through a unit operation plan, assisted perhaps by a well-spacing regulation.

It is probable that no more than two billion cubic feet per month would have been the ideal production rate from the Driftwood-Benezette field. Gas companies taking gas from this field must contract for vast quantities of gas from the Southwest to meet commitments during the winter months. Furthermore, the nature of pipeline operations as well as economic factors in the producing Southwest demand the establishment of long-term contracts with little or no seasonal variations in gas deliveries. This requires the delivery of large quantities of gas to this area during the summer months which must be stored in underground reservoirs. It is therefore obvious that the most economical rate to extract gas from this field would be a long-term rate necessary to augment deliveries from the Southwest with a minimum of storing required.

According to curve AB (Figure 6), two billion cubic feet per month could have been produced early in the productive life of the field ( $P_f = 4600$ ) with 27 wells producing at 25 per cent of open-flow capacity, and with 100 wells at this capacity five years later when the 120 billion cubic feet produced would have caused the reservoir pressure to drop to about 2400 pounds per square inch (Figure 4). At 50 per cent open-flow capacity, only half of these wells would be required, and 100 wells would produce two billion cubic feet or more per month until 175 billion cubic





feet of gas had been produced. Assuming that the flow rate could reach a maximum at the lower pressures without causing significant damage to the wells or the formation, 100 wells would sustain the 2 billion cubic feet per month rate for almost nine years or until 210 billion cubic feet of gas had been produced. Does not this appear more efficient and logical than has been the actual practice of drilling 277 producing wells, with more to come, to obtain the flow rate shown in Figure 3? The above comparison of actual practices with those which might have been employed under unit operations or under well spacing regulations does not show a comparison of ultimate recovery losses. It was illustrated in Section V, C that there should be at least 20 billion cubic feet of gas lost because of inefficient production practices. Though structural conditions in the reservoir might not permit such high ultimate recovery in either the actual or the ideal case, it is probable that unit operations or adequate well spacing regulations would provide for more efficient exploration and thereby for a production rate closely approaching that shown by the curve AB (Figure 5).

It is estimated that about 20 billion cubic feet of gas would have been lost in the case of at least two wells per acre had it been possible to produce at a rate of 2 billion cubic feet per acre per year. This will amount to 40 billion cubic feet.

(a) There have been numerous relatively minor losses due to expansion of gas as it rises to the surface, to the operation of compressors, and to the operation of valves and other flow production accessories, and to the operation of the wells.

(b) There have been losses due to the operation of the wells, and to the operation of the valves and other flow production accessories, and to the operation of the wells.

fact of gas had been produced. Assuming that the flow rate could reach a maximum of the lower pressure without causing significant damage to the wells or the formation, 100 wells would maintain the 3 billion cubic feet per month rate for almost nine years at which 210 billion cubic feet of gas had been produced. But not this appears more efficient and logical than has been the actual practice of drilling 575 producing wells, which were so close, to obtain the flow rate shown in Figure 1.

The above comparison of actual practices with those which might have been applied which will optimize or better will optimize operations does not show a comparison of ultimate recovery losses. It was estimated in Section V, C that there should be at least 30 billion cubic feet of gas lost because of inefficient production practices. These estimated conditions in the reservoir might not permit such high ultimate recovery in either the actual or the ideal case, it is probable that such operations or operations will optimize operations would provide for more efficient operations and thereby for a production rate closely approximating that shown by the curve in Figure 6.



## B. Economic Aspects

### 1. General

The economic aspects of production practices may be illustrated roughly as follows:

(a) Before this reservoir is abandoned there will probably have been 300 producing wells drilled — 200 more than is conservatively estimated to be the ideal as stated in the previous section. At \$75,000 per well, this will amount to an unnecessary expenditure of \$15,000,000.

(b) It is estimated that at least 60 billion cubic feet of gas will have been stored and re-extracted beyond that which would have been necessary at the two billion per month rate. At an estimated cost of five cents per thousand cubic feet for storing and re-extracting, this will amount to \$3,000,000.

(c) Twenty billion cubic feet of gas estimated to be lost due to open flow production practices, at an estimated net value of about ten cents per M cubic feet<sup>22</sup> will amount to a loss of \$2,000,000.

(d) It is estimated that about 75 billion cubic feet of gas would have increased in value by at least two cents per M cubic feet had it been possible to produce this gas on a seasonal contract or at a slower rate. This will amount to \$1,500,000.

(e) There have been numerous relatively minor excessive expenditures, such as expenses for operating compressor stations, additional well maintenance costs due to open flow production practices, excess gathering lines, etc.

In view of the foregoing illustration, it is reasonable to assume that \$20,000,000 have or will be wasted by the production practices employed in the Driftwood-Benezette gas reservoir. Furthermore, a large

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## I. General

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to open flow production practices, at an estimated net value of about ten

cents per M cubic feet<sup>22</sup> will amount to a loss of \$2,000,000.

(d) It is estimated that about 75 billion cubic feet of gas would

have increased in value by at least two cents per M cubic feet had it been

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(e) There have been numerous relatively minor excessive expendi-

tures, such as expenses for operating compressor stations, additional well

maintenance costs due to open flow production practices, excess gather-

ing lines, etc.

In view of the foregoing illustration, it is reasonable to assume

that \$20,000,000 have or will be wasted by the production practices em-

ployed in the Whitewood-Benvenue gas reservoir. Furthermore, a large

portion of these losses will be paid by the consumer in the form of high gas prices or in taxes to make up for the losses from state-owned tracts.

## 2. Private Landowners

Much of the land overlying this reservoir is privately owned small tracts of one acre or less. Such a landowner's fair share of the gas, considering 40,000 acres total and 280 billion cubic feet of gas as recoverable, is 7,000 M cubic feet. At one-eighth royalty this figure is further reduced to roughly 900 M cubic feet, which would amount to \$247.50 at the current price of 27½ cents per M cubic feet. It is conservatively estimated that many small tract landowners have or will receive at least a hundred times this figure. Their excess profits obviously resulted in losses from less densely drilled areas, which in this field are mostly state-owned tracts.

Therefore, it is the opinion of the Commission that the proposed plan will prevent the loss of income, material, and valuable resources, and will also insure the protection of appropriate rights of landowners.

The results of the study conducted by the Commission and the various agencies are shown in the report of this study. The average cost of gas, however, should not be too high compared with other sources of gas. It is felt that without the study made by the Commission the losses would be greatly increased. The Commission feels that the study made by the Commission is a valuable contribution to the study of gas resources.

The Commission feels that the study made by the Commission is a valuable contribution to the study of gas resources.

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portion of these losses will be paid by the Government in the form of high interest loans to the Government.

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## VII. CONCLUSIONS AND RECOMMENDATIONS

It is concluded that there have been about 200 excess wells drilled in the Briftwood-Benezette field; that there could not possibly have been a fair and equitable distribution of the gas among the various landowners; that very probably there have or will be large quantities of gas left in the reservoir because of open-flow production practices; that sound engineering principles are not observed in gaging wells and in evaluating their performance, and that all of these are directly attributable to the lack of petroleum regulatory statutes in Pennsylvania. It is further concluded that the general public supports a large share of the inequities, gas losses and excess expenses either in higher gas prices or in decreased revenue from publicly owned land.

The obvious recommendation, therefore, is that the citizens of Pennsylvania demand the enactment of state statutes which will prevent this waste of manpower, materials, and petroleum resources, and which will insure the protection of correlative rights of landowners.

The details of the varied petroleum conservation measures and unitization statutes are beyond the scope of this paper. The average citizen, however, should not be so much concerned with these details as by the fact that nothing is being done to remedy the current inefficient and unfair production practices. Citizens should place their faith in an Oil and Gas Commission appointed for the purpose of recommending appropriate conservation and unitization statutes and for enforcing the statutes after they are enacted. No person need fear monopolistic practices or the deprivation of his property without the due process of law. He is protected from these under federal law.

# III. CONCLUSIONS AND RECOMMENDATIONS

It is concluded that there have been about 100 cases with  
died in the British-American field; that there could not possibly  
have been a fair and equitable distribution of the two among the various  
countries; that very probably there have or will be large quantities of  
gas left in the reservoir because of open-flow production practices; that  
some engineering techniques are not observed in logging wells and in  
evaluating their performance, and that all of these are directly related  
to the lack of petroleum regulatory statutes in Pennsylvania. It  
is further concluded that the general public supports a large share of  
the investigation, gas losses and various expenses either in higher gas prices  
or in increased revenues from publicly owned lands.  
The obvious recommendation, therefore, is that the citizens of  
Pennsylvania demand the enactment of state statutes which will prevent  
this waste of resources, materials, and petroleum resources, and which  
will insure the protection of certain rights of landowners.  
The details of the various petroleum conservation measures and  
utilization policies are beyond the scope of this paper. The average  
citizen, however, should not be so much concerned with these details as  
by the fact that nothing is being done to remedy the current ineffectual  
and unfair production practices. Citizens should place their faith in an  
oil and gas commission appointed for the purpose of recommending  
appropriate conservation and utilization statutes and for enforcing the  
statutes already enacted. It is recommended that appropriate  
provisions in the constitution of the property without the process of  
law be introduced into these under federal law.

It is additionally recommended that the State immediately institute a program to acquire, compile and correlate information needed for accurate engineering studies, and to make this information readily available to all interested parties. No information relating to well production should be confidential. The very least that should be done is the enactment of a law requiring that all gas wells be shut in for a minimum of 48 hours once a year and that shut-in pressures be recorded and reported to an appropriate state regulatory body. Open-flow capacities, or flow rates against stated back pressures, should be recorded at the time wells are shut in, and likewise reported. Though this information will not suffice for accurate computation of the wells' performance by the Bureau of Mines back-pressure method, it will provide for considerably more accurate engineering studies than are currently possible. This recommendation would be superfluous if adequate petroleum conservation laws were enacted, for effective conservation presupposes a requirement for accurate knowledge of both the gas reservoir and the producing wells, which can only be gained from extensive and accurate data.



It is additionally recommended that the State immediately create a program to acquire, compile and coordinate information needed for accurate engineering studies, and to make this information readily available to all interested parties. No information relating to well production should be confidential. The very least that should be done is the maintenance of a log recording that all gas wells be shut in for a minimum of 48 hours once a year and that shut-in pressures be recorded and reported to an appropriate state regulatory body. Open-flow operations, or flow rates against stated back pressures, should be recorded at the same wells and must be, and likewise reported. Through this information will not suffice for accurate comparison of the wells' performance by the Bureau of Mines and pressure records, it will provide for considerably more accurate engineering studies than are currently possible. This recommendation would be applicable if accurate bottom hole pressure data were needed, for effective conservation programs a requirement for accurate knowledge of both the reservoir and the producing wells, which can only be gained from extensive and accurate data.





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## APPENDIX I

Producing Wells in the Driftwood-Benezette Gas Field

Well No. and Area <sup>a</sup>	Name and Number	Drilling Completed	Depth	Flow Mcf/day	Initial W.H.P. psig
1-A	S.C. Eaton, Jr. #1 (Sylv.)	9-15-51	5922	4,000	3925
11-H	Bearpaw Rod & Gum #1 (Fralich)	5-5-52	5876	4,900	3950
23-O	B & O #1 (Plymouth)	6-23-52	5952	80	-
25-A	Caldwell #1	7-9-52	5886	1,000	3500
29-A	Mix Run School Lot #1	7-25-52	5830	3,300	3950
36-H	J. W. Hoate #1	8-18-52	6143	6,880	850
37-A	B. R. & G. #1 (Fox)	8-29-52	5802	3,200	2850
38-A	Caldwell #1	9-10-52	5846	700	-
41-A	Caldwell #2	10-3-52	5857	3,400	2700
43-O	McMillan Est. #1 (Delta)	10-10-52	5820	6,100	3400
45-O	S. C. Eaton #6	10-13-52	5996	3,500	3340
47-A	St. 2 Tr. 19	10-27-52	7051	1,000	3650
50-A	Hoate #1 (Fox)	11-14-52	5862	1,200	3050
52-O	S. C. Eaton, Jr. #4	11-26-52	5903	838	2700
53-A	S. C. Eaton, Jr. #2 (Sylv)	12-3-52	6227	1,620	2500
54-H	St. 1 Tr. 20	12-8-52	5927	4,500	3655
55-O	S. C. Eaton, Jr. #2 (MYSN)	12-9-52	5944	2,100	2250
57-S	Charlton Mt. Club #1	12-30-52	6975	2,800	3810
58-H	St. 2 Tr. 20	12-31-52	6408	1,900	3200
59-A	S. Hoate #1 (Pamco)	1-2-53	5840	2,560	1775
60-A	S. Hoate #2	1-2-53	5851	2,166	2925
61-O	Eaton #7	1-3-53	5822	2,274	2170
62-A	Brookbank #1	1-5-53	5887	3,100	3250
63-H	H. A. Hoate #1 (Sylvania)	1-10-53	6072	177	660
64-B	H. L. Pearceall #1	2-2-53	5978	3,000	3400
65-A	H. A. Hoate #2	2-18-53	5984	134	1520
66-H	Clyde L. Smith #1	2-20-53	6075	239	-
67-O	S. C. Eaton #5	2-20-53	5980	2,386	1805
69-F	Wm. Wairing #1	3-7-53	6153	713	800
72-F	W. A. Thursty #1	3-24-53	6101	8,000	4000
74-Q	Sagamore Hunt Club #1	4-1-53	6893	18,200	2150
75-O	Catherine Bartoletto #1	4-11-53	6134	9,500	3950
77-H	Eaton #8	4-21-53	6390	3,450	1740
79-S	Charlton Mt. Club #3	5-2-53	6936	17,000	-
80-H	Clyde Smith #2	5-14-53	6150	1,017	1310
81-H	Eaton #9	5-15-53	6810	2,600	1745
82-B	B & O #2	5-27-53	5870	1,200	1900
84-S	Charlton Mt. Club #2	6-1-53	6943	5,250	3300
85-R	Sagamore Hunt Club #1	6-2-53	6903	8,900	3675
86-S	Johnson Est. #1	6-3-53	6307	9,800	4020
88-B	St. 4 Tr. 19	6-10-53	6019	300	-
89-H	Hoate #3	6-12-53	6592	1,038	1400
92-O	Charles Duell #1	6-20-53	6168	400	2860

<sup>a</sup>Wells shown by number and area in Figure 2. Missing numbers in the sequence indicate dry holes drilled in or near the field.

# APPENDIX I

Producing Wells in the Oilfield - Summary for 1964

Well No.	Prod. (bbls)	Conj. (bbls)	Water (bbls)	Gas (bbls)	Notes
1-1	1000	1000	1000	1000	Producing
1-2	1000	1000	1000	1000	Producing
1-3	1000	1000	1000	1000	Producing
1-4	1000	1000	1000	1000	Producing
1-5	1000	1000	1000	1000	Producing
1-6	1000	1000	1000	1000	Producing
1-7	1000	1000	1000	1000	Producing
1-8	1000	1000	1000	1000	Producing
1-9	1000	1000	1000	1000	Producing
1-10	1000	1000	1000	1000	Producing
1-11	1000	1000	1000	1000	Producing
1-12	1000	1000	1000	1000	Producing
1-13	1000	1000	1000	1000	Producing
1-14	1000	1000	1000	1000	Producing
1-15	1000	1000	1000	1000	Producing
1-16	1000	1000	1000	1000	Producing
1-17	1000	1000	1000	1000	Producing
1-18	1000	1000	1000	1000	Producing
1-19	1000	1000	1000	1000	Producing
1-20	1000	1000	1000	1000	Producing
1-21	1000	1000	1000	1000	Producing
1-22	1000	1000	1000	1000	Producing
1-23	1000	1000	1000	1000	Producing
1-24	1000	1000	1000	1000	Producing
1-25	1000	1000	1000	1000	Producing
1-26	1000	1000	1000	1000	Producing
1-27	1000	1000	1000	1000	Producing
1-28	1000	1000	1000	1000	Producing
1-29	1000	1000	1000	1000	Producing
1-30	1000	1000	1000	1000	Producing
1-31	1000	1000	1000	1000	Producing
1-32	1000	1000	1000	1000	Producing
1-33	1000	1000	1000	1000	Producing
1-34	1000	1000	1000	1000	Producing
1-35	1000	1000	1000	1000	Producing
1-36	1000	1000	1000	1000	Producing
1-37	1000	1000	1000	1000	Producing
1-38	1000	1000	1000	1000	Producing
1-39	1000	1000	1000	1000	Producing
1-40	1000	1000	1000	1000	Producing
1-41	1000	1000	1000	1000	Producing
1-42	1000	1000	1000	1000	Producing
1-43	1000	1000	1000	1000	Producing
1-44	1000	1000	1000	1000	Producing
1-45	1000	1000	1000	1000	Producing
1-46	1000	1000	1000	1000	Producing
1-47	1000	1000	1000	1000	Producing
1-48	1000	1000	1000	1000	Producing
1-49	1000	1000	1000	1000	Producing
1-50	1000	1000	1000	1000	Producing

## APPENDIX I (Continued)

Well No. and Area	Name and Number	Drilling Completed	Depth	Flow McF/day	Initial W.H.P. psig
93-N	H. A. Moate #5	6-22-53	6040	1,473	-
94-N	H. A. Moate #4	6-22-53	6190	2,100	2575
96-F	Bateman #1	6-27-53	6112	16,980	3880
97-F	B & O RH #1 (Mid-Atlantic)	7-11-53	6087	12,250	3600
98-A	B & O #1 (Chs. Sample)	7-14-53	5880	4,500	2300
99-O	McMillian #1 (Kane)	7-22-53	5994	1,100	880
101-F	Theo. Sten #1	7-22-53	6065	8,500	3720
102-F	O. Johnson #1	7-23-53	6202	9,250	3750
103-K	Pearsall #1 (Fralich)	7-28-53	6974	25,500	3700
104-H	Van Voorhees #1 (Simon)	7-29-53	6099	9,600	3880
105-F	J. Miller #1	8-1-53	6048	7,000	3745
106-S	Charleroi #6	8-7-53	6218	2,700	3720
107-S	St. 4 Tr. 29	8-10-53	6870	2,075	3550
108-F	B. Johnson #1	8-11-53	6196	5,000	3020
109-F	P.R.R. #1	8-11-53	-	4,200	-
110-F	B. Johnson #2	8-11-53	6119	4,000	3170
111-F	J. Miller #2	8-14-53	6122	5,200	3000
112-F	Grafton (Camp Shanty) #1	8-14-53	6146	5,750	3000
113-A	H. A. Moate #6	8-14-53	6023	3,000	2250
114-S	R. Weiss #1	8-16-53	6141	5,000	2500
115-H	Pontzer #1	8-18-53	6116	13,700	3000
116-F	Sam Enz #1	8-18-53	6110	9,600	3700
117-H	Brookbank #2	8-20-53	5896	2,600	2300
118-S	Bartolette #2	8-20-53	6269	10,500	-
119-F	Overturf #1	8-21-53	-	9,000	-
120-S	A. J. Moser #1	8-21-53	5995	2,300	3100
121-S	Vause #1	8-22-53	6109	3,125	3925
122-F	Nicolo Pascuzzi #1	8-24-53	6160	1,800	3200
123-F	Thunderbird Camp #1	8-25-53	6137	5,700	2860
124-H	Johnson Est. #3	8-25-53	6263	16,000	3200
125-H	Mackey #1	8-28-53	6105	14,500	-
126-I	Stiveson #1	8-31-53	6163	5,731	3000
127-I	W. A. Thurby #2	9-1-53	6276	5,300	2725
128-F	J. R. Roger #1	9-1-53	6172	5,700	2750
129-H	Gambel #1	9-3-53	6121	34,000	3360
130-I	Steffy #1	9-4-53	6215	7,000	3000
132-S	St. 2 Tr. 29	9-9-53	6947	4,332	3220
133-H	Johns #1	9-10-53	6073	8,530	3050
134-A	P.R.R. #2	9-10-53	5860	1,800	1000
135-03	St. 1 Tr. 33	9-13-53	6392	7,350	3920
136-Q	Sagamore Hunt #4	9-22-53	6890	2,067	-
137-O	Overturf #2	9-25-53	6088	14,700	2500
138-H	H. Bleish #1	9-26-53	7011	7,300	-
139-S	Rothrock #2	9-28-53	6108	12,300	2590
140-Q	B & O #2 (Mid-Atlantic)	9-28-53	6131	3,000	-
141-F	Coleman #1	9-29-53	6147	5,300	1960
142-H	Rothrock #3	9-30-53	6128	8,600	-

(Continued)

1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	2096	2097	2098	2099	2100
1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050	2051	2052	2053	2054	2055	2056	2057	2058	2059	2060	2061	2062	2063	2064	2065	2066	2067	2068	2069	2070	2071	2072	2073	2074	2075	2076	2077	2078	2079	2080	2081	2082	2083	2084	2085	2086	2087	2088	2089	2090	2091	2092	2093	2094	2095	2096	2097	2098	2099	2100

## APPENDIX I (Continued)

Well No. and Area <sup>a</sup>	Name and Number	Drilling Completed	Depth	Flow Mcf/day	Initial W.H.P. psig
143-F	Charleroi Mt. Club #5	9-30-53	6305	8,000	2800
144-H	Johnson Est. #2 (Keta)	10-1-53	6497	6,800	2600
145-F	Hot Shot Camp #1	10-3-53	6160	3,470	1980
146-H	Van Voorhees #1 (Kahle)	10-3-53	6114	11,000	2575
147-F	Mountain Camp #1	10-6-53	6190	3,750	1900
151-F	Ahlborn Coal Co. #1	10-12-53	6960	28,000	-
152-I	Thurby #4	10-13-53	6394	7,960	2800
152-G	Charleroi #10	10-14-53	6118	16,000	2550
155-E	Pasley Ober #1	10-17-53	6064	4,750	3600
156-AA	St. 2 Tr. 25	10-20-53	6999	6,000	3260
157-MM	St. 1 Tr. 32	10-21-53	7034	1,313	3140
158-L	St. 6 Tr. 20	10-21-53	-	3,400	3500
159-Z	St. 5 Tr. 29	10-24-53	6914	14,850	3290
160-K	Pearsall #1 (Sylvania)	10-26-53	6975	6,000	3375
161-H	Rothrock #1	10-26-53	6099	7,000	-
162-P	St. 2 Tr. 27	10-30-53	6935	10,849	3440
163-D	D. Hindrobariak #1	10-31-53	6092	1,438	-
164-X	St. 1 Tr. 34 A	11-2-53	6975	8,500	3625
165-FF	St. 9 Tr. 29	11-2-53	6900	14,671	3620
166-AA	St. 2 Tr. 30	11-2-53	6977	5,000	3460
167-G	Rothrock #5	11-2-53	6112	8,000	1850
168-F	Green #1	11-3-53	6154	3,300	1600
169-H	Charleroi R & G #7	11-4-53	6102	26,000	3250
171-P	Sam Ruz #1 (Shearer)	11-5-53	6310	5,900	-
172-R	Billings-Mason #2	11-10-53	6062	4,800	-
173-Q	St. 1 Tr. 27	11-11-53	6936	10,500	3210
175-Q	Sagamore Hunt Cl. #3	11-13-53	6128	22,500	3085
176-F	Corz Bennett #1	11-17-53	6185	1,474	1600
177-R	St. 1 Tr. 28	11-20-53	6938	20,100	3210
178-H	Rothrock #4	11-22-53	6119	11,250	-
179-R	St. 3 Tr. 29	11-25-53	6965	4,642	3210
180-H	B & R #4 (Mid-Atlantic)	11-25-53	6069	4,900	1500
181-AA	St. 1 Tr. 30	11-25-53	6566	412	3000
182-J	St. 1 Tr. 26	11-25-53	6903	4,073	3225
183-F	Bolta #1	11-26-53	6157	4,200	1500
184-F	Howry #1	11-26-53	6842	7,000	-
185-F	Lawrence Winslow #1	11-28-53	6891	3,373	2600
186-H	Pontner #2	12-3-53	6175	8,200	1450
187-X	Denver Miller #1	12-3-53	6885	8,200	3750
188-I	Allegheny Camp #1	12-3-53	6169	3,600	1450
189-G	Ahlborn Coal #1	12-3-53	6999	8,400	3150
190-F	Overturf #3	12-4-53	6240	1,100	-
191-R	Sagamore Hunt Cl. #2	12-4-53	-	6,500	3100
192-I	Thurby #5	12-4-53	6175	8,000	2100
193-H	Charleroi #9	12-5-53	6187	10,750	-
194-F	B & O RR #5	12-5-53	6062	4,200	2400
195-F	Lewis Jourdain #1	12-7-53	6199	1,350	1500
197-F	Arthur Davis #1	12-9-53	6212	2,700	1450



Roll No.	Name	Age	Height	Weight	Complexion	Religion	Marital Status	Education	Occupation	Address	Phone No.
1001	John Doe	25	5'8"	180	Fair	Christian	Married	High School	Teacher	123 Main St, New York, NY	555-1234
1002	Jane Smith	22	5'6"	150	Fair	Christian	Single	College	Student	456 Oak St, New York, NY	555-5678
1003	Robert Johnson	30	6'0"	200	Dark	Muslim	Married	University	Engineer	789 Pine St, New York, NY	555-9012
1004	Maria Garcia	28	5'4"	140	Dark	Catholic	Married	High School	Nurse	101 Elm St, New York, NY	555-3456
1005	David Lee	24	5'9"	170	Fair	Buddhist	Single	College	Software Developer	202 Maple St, New York, NY	555-7890
1006	Sarah Kim	26	5'7"	160	Fair	Christian	Married	University	Researcher	303 Cedar St, New York, NY	555-2345
1007	Michael Brown	29	6'1"	190	Dark	Christian	Married	High School	Police Officer	404 Birch St, New York, NY	555-6789
1008	Emily White	23	5'5"	130	Fair	Christian	Single	College	Artist	505 Walnut St, New York, NY	555-0123
1009	Christopher Davis	31	6'2"	210	Dark	Muslim	Married	University	Lawyer	606 Spruce St, New York, NY	555-4567
1010	Ashley Miller	27	5'8"	165	Fair	Christian	Single	College	Journalist	707 Hickory St, New York, NY	555-8901
1011	Benjamin Wilson	25	5'9"	175	Fair	Buddhist	Married	High School	Chef	808 Ash St, New York, NY	555-2345
1012	Olivia Taylor	24	5'6"	145	Fair	Christian	Single	College	Designer	909 Elm St, New York, NY	555-6789
1013	Lucas Anderson	28	6'0"	195	Dark	Muslim	Married	University	Physician	1010 Maple St, New York, NY	555-0123
1014	Sophia Martinez	26	5'7"	155	Fair	Catholic	Married	High School	Translator	1111 Cedar St, New York, NY	555-4567
1015	Isaac Thompson	32	6'3"	220	Dark	Christian	Married	University	Business Owner	1212 Birch St, New York, NY	555-8901
1016	Grace Roberts	25	5'8"	160	Fair	Buddhist	Single	College	Writer	1313 Walnut St, New York, NY	555-2345
1017	Samuel Clark	29	6'1"	200	Dark	Christian	Married	High School	Construction Worker	1414 Spruce St, New York, NY	555-6789
1018	Madeline Lewis	27	5'9"	150	Fair	Muslim	Single	College	Marketing Specialist	1515 Ash St, New York, NY	555-0123
1019	Jonathan Hall	30	6'2"	210	Dark	Christian	Married	University	Professor	1616 Elm St, New York, NY	555-4567
1020	Chloe Young	24	5'6"	140	Fair	Buddhist	Single	College	Event Planner	1717 Maple St, New York, NY	555-8901



## APPENDIX I (Continued)

Well No. and Area*	Name and Number	Drilled Completed	Depth	Flow Gaf/day	Initial W.H.P. psig
198-T	St. 6 Tr. 29	12-10-53	6965	17,196	3100
199-F	Navis & Snyder #1	12-11-53	6136	2,560	1450
200-3	Ahlborn Coal #2	12-14-53	6396	2,300	2900
201-Q	St. 3 Tr. 27	12-23-53	7015	4,333	2850
202-AA	St. 3 Tr. 28	12-26-53	6964	1,100	3150
203-H	Oumble #2	12-27-53	6172	10,000	1250
205-F	Camp Kield #1	1-2-54	6137	2,646	1340
206-W	Wm. Laughlin #1	1-2-54	6258	3,125	3750
207-E	Sas Run #2 (Mid-Atlantic)	1-2-54	6103	7,810	3100
208-E	Cooks Camp #1	1-4-54	6146	4,275	3600
209-AA	St. 8 Tr. 29	1-5-54	6940	342	3380
210-Y	Stiverson #1	1-6-54	6380	7,500	2590
211-T	Charlrot H & O #4	1-6-54	6380	7,500	2590
212-EE	St. 1 Tr. 31	1-8-54	7081	140	-
214-D	Schiller #1	1-13-54	6102	3,000	-
215-F	St. 1 Tr. 34	1-15-54	6383	2,388	1900
217-C	H. & M. Mason #2	1-15-54	6140	6,000	3750
216-F	King Gold Club #1	1-15-54	6116	2,000	1400
218-T	St. 7 Tr. 29	1-26-54	6893	9,811	-
219-F	Pearsall #2 (Sylvania)	1-26-54	6223	24,300	2723
220-T	Ahlborn Coal #2	1-26-54	6935	4,500	2150
221-F	Wm. Woodring #1 (Haddock)	1-27-54	6224	6,000	1600
222-F	Camp Liria #1	1-30-54	6183	1,650	1050
223-H	Charlrot #8	2-1-54	6204	7,300	-
225-03	St. 5 Tr. 31	2-4-54	7007	4,875	3500
227-H	B & O #6	2-5-54	6118	6,100	-
228-S	B & O #2 (Gas. Sample)	2-10-54	6973	600	1800
229-S	Sas Run #3	2-11-54	6224	1,438	3150
230-T	St. 12 Tr. 29	2-11-54	6940	3,523	2800
231-3	Ahlborn Coal #2	2-11-54	6985	7,000	2125
232-AA	St. 1 Tr. 29	2-12-54	6905	4,760	2510
233-H	Thurby #6	2-13-54	6923	4,100	1450
234-Y	Dollinger #1	2-13-54	6442	1,178	3580
236-W	Heffelfinger #1	2-15-54	6254	557	-
239-Q	Wm. Shuck #1	2-19-54	6052	1,438	3000
240-W	Shingledecker #1	2-20-54	6259	1,300	3750
241-00	St. 1 Tr. 36	3-1-54	7155	12,800	3830
243-W	St. 6 Tr. 31	3-4-54	6444	40,234	3560
245-D	Dents Run Coal #1	3-10-54	6092	400	2340
246-P	St. 5 Tr. 27	3-12-54	6159	82	1650
247-F	B & O #1 (J.I. Shearer)	3-13-54	6132	557	950
248-G	Ahlborn Coal #3	3-16-54	6993	5,538	1850
249-R	St. 4 Tr. 28	3-16-54	6998	4,770	2050
252-EE	St. 1 Tr. 34	3-22-54	7295	125	-
254-W	St. 1 Tr. 38	3-25-54	6226	5,454	3850
255-L	St. 2 Tr. 25	3-30-54	6995	4,860	2600
256-P	St. 4 Tr. 27	3-30-54	7122	13,000	1850
257-CC	St. 5 Tr. 28	3-39-54	6911	6,000	1850

(continued) 1 21705-94

Index No.	Year	Volume	Page	Page	Page	Page
1001	1901	1001	1001	1001	1001	1001
1002	1902	1002	1002	1002	1002	1002
1003	1903	1003	1003	1003	1003	1003
1004	1904	1004	1004	1004	1004	1004
1005	1905	1005	1005	1005	1005	1005
1006	1906	1006	1006	1006	1006	1006
1007	1907	1007	1007	1007	1007	1007
1008	1908	1008	1008	1008	1008	1008
1009	1909	1009	1009	1009	1009	1009
1010	1910	1010	1010	1010	1010	1010
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1015	1915	1015	1015	1015	1015	1015
1016	1916	1016	1016	1016	1016	1016
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1018	1918	1018	1018	1018	1018	1018
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1097	1997	1097	1097	1097	1097	1097
1098	1998	1098	1098	1098	1098	1098
1099	1999	1099	1099	1099	1099	1099
1100	2000	1100	1100	1100	1100	1100

## APPENDIX I (Continued)

Well No. and Area	Name and Number	Drilling Completed	Depth	Flow Wcf/day	Initial W.H.P. psig
258-MH	St. 4 Tr. 33	4-3-54	6201	4,854	3500
259-I	Thurby #7	4-3-54	6918	21,000	1450
260-Y	St. 5 Tr. 34A	4-10-54	6394	8,500	2825
261-U	Bleish #3	4-12-54	6941	968	1550
262-T	Ahlborn Coal #4	4-12-54	6868	4,000	-
263-R	Ray Laughlin #1	4-13-54	6254	852	2700
268-X	St. 3 Tr. 31	4-16-54	6381	7,810	3260
269-R	St. 8 Tr. 26	4-18-54	6741	2,427	2000
270-Q	Sagsmore #5	4-18-54	6475	6,400	1775
272-II	St. 2 Tr. 38	4-22-54	6625	6,066	3625
274-T	Ahlborn Coal #5	4-27-54	6988	4,000	1575
275-Y	St. 1 Tr. 34B	4-28-54	7151	1,000	3550
276-Z	St. 2 Tr. 34A	4-28-54	7060	368	1950
277-OO	St. 3 Tr. 32	4-29-54	7176	5,523	2980
280-W	Bleish #4	5-1-54	7001	8,500	1425
281-X	Parks #1 (Yonke et al)	5-3-54	6428	3,250	2875
282-E	Billings and Maxon #1	5-3-54	6119	4,600	2160
284-P	Bateman #1	5-5-54	6146	696	700
285-Q	St. 7 Tr. 26	5-7-54	6060	2,350	2150
286-X	Danielson #1	5-8-54	6254	475	3000
287-W	St. 1 Tr. 25	5-12-54	6992	7,035	2450
288-OB	St. 2 Tr. 33	5-17-54	7019	4,151	3160
289-W	Logue #1	5-17-54	6247	1,400	2500
290-U	St. 13 Tr. 29	5-19-54	6892	4,900	2800
291-WB	St. 5 Tr. 30	5-20-54	7024	5,731	2560
292-X	Parks #1 (Layton)	5-20-54	6393	2,438	2500
294-J	St. 6 Tr. 26	5-21-54	6929	3,021	2450
295-T	Charleroi #12	5-27-54	7039	4,400	1850
296-X	St. 10 Tr. 29	5-27-54	6944	850	2500
297-X	St. 4 Tr. 34A	5-29-54	7112	250	1650
298-DO	St. 6 Tr. 6	6-1-54	7080	3,479	2940
299-MH	St. 5 Tr. 33	6-1-54	6313	14,210	2916
301-J	St. 2 Tr. 26	6-5-54	6934	2,085	2175
302-Z	St. 3 Tr. 34A	6-7-54	7029	4,272	2650
304-K	St. 9 Tr. 26	6-9-54	6969	4,973	2050
305-OO	St. 1 Tr. 34C	6-10-54	7106	1,217	2625
306-U	St. 14 Tr. 29	6-10-54	6809	38,000	3125
307-WH	St. 2 Tr. 32	6-10-54	7111	1,174	1790
308-KK	St. 3 Tr. 38	6-11-54	6220	38,000	3125
309-P	Holben #1	6-12-54	6147	600	-
310-DO	St. 2 Tr. 34C	6-19-54	7102	12,572	3300
311-K	H. L. Pearsall #4	6-21-54	6331	2,200	1820
312-MH	St. 2 Tr. 37	6-21-54	6224	4,450	2980
313-I	Thurby #3	6-22-54	6939	1,500	-
315-X	Parks #1 (Bailey)	6-26-54	6366	1,800	2060
316-Q	Sagsmore #7	6-28-54	6491	2,300	1425
319-D	St. 11 Tr. 26	7-2-54	6208	189	2100
320-I	Thurby #6	7-7-54	7046	700	1300



## APPENDIX I (Continued)

Well No. and Area	Name and Number	Drilled Completed	Depth	Flow Wcf/day	Initial W.H.P. psig
322-I	St. 12 Tr. 26	7-13-54	6918	2,218	2050
323-LL	St. 6 Tr. 33	7-16-54	6366	1,857	1620
324-KK	St. 4 Tr. 38	7-20-54	6287	213	2275
325-X	St. 16 Tr. 29	7-24-54	6373	920	2450
326-Y	Pascuzzi #1	7-24-54	6063	2,463	1300
327-00	St. 4 Tr. 36	7-29-54	7095	990	1850
328-BB	St. 4 Tr. 30	7-29-54	6920	2,936	-
329-T	St. 17 Tr. 29	7-30-54	7004	42,000	1910
332-E	St. 10 Tr. 26	8-2-54	6866	1,279	2350
334-FF	St. 11 Tr. 31	8-13-54	7102	1,000	2500
335-X	Herman Morre #1	8-14-54	6232	4,500	3700
337-KK	St. 1 Tr. 29	8-24-54	6473	6,100	3050
339-V	Denver Miller #3	9-3-54	6750	2,800	3150
340-X	Roosensteel #1	9-4-54	6232	3,300	3100
341-LL	St. 8 Tr. 33	9-14-54	6303	5,741	1340
342-WH	St. 3 Tr. 33	9-15-54	7007	996	1990
343-R	Sagamore #6	9-16-54	6417	2,542	1280
344-W	St. 7 Tr. 31	9-18-54	6315	1,081	1580
346-V	Dollinger #1	10-8-54	6262	5,080	2650
349-LL	St. 9 Tr. 33	10-11-54	6420	239	1410
350-B	St. 7 Tr. 20	10-11-54	6907	1,271	1450
351-Y	St. 11 Tr. 29	10-12-54	6950	3,373	1650
353-B	Billings and Mason #3	10-21-54	6830	2,250	1530
354-V	Steve Rupprecht #1	10-27-54	6902	4,200	2290
356-L	Pearcell #5	10-29-54	7021	1,885	1425
357-W	Paul Chase #1	11-6-54	6341	10,833	3600
358-V	Dollinger #2	11-9-54	6760	3,769	2310
359-W	Craffatt (Ross Hrs.) #1	11-13-54	6204	2,166	3175
362-C	H. & G. Mason #1	11-29-54	6932	134	-
363-KK	St. 2 Tr. 39	11-31-54	7145	1,246	-
364-01	St. 2 Tr. 34	12-3-54	7113	680	1400
365-X	Claude Chase #1 (Kahle)	12-10-54	6239	3,921	1507
366-V	Walter Tuxie #1	12-13-54	6216	4,047	1700
368-W	St. 3 Tr. 37	12-20-54	6884	3,425	3500
370-X	Boosters Club #1	1-17-55	6182	5,500	2500
371-X	Crown Control #1	1-17-55	6220	1,600	2160
372-W	St. 4 Tr. 37	1-19-55	7029	5,731	2725
373-03	St. 11 Tr. 33	2-22-55	6283	4,275	-
374-II	St. 5 Tr. 38	2-23-55	6943	2,900	1800
375-II	St. 5 Tr. 37	2-25-55	7076	894	2850
376-W	Hall Chase #2	2-26-55	6598	3,000	2400
377-Z	St. 13 Tr. 29	3-3-55	7029	4,775	1120
378-00	St. 7 Tr. 30	3-10-55	7225	696	1140
379-Y	St. 20 Tr. 29	3-16-55	6508	4,055	1125



(b)(7)(C), (b)(7)(D) X 2025-2026

Year	Month	Day	Time	Location	Remarks
1900	Jan	1	10:00	St. Paul	Arrived
1900	Jan	2	10:00	St. Paul	Departed
1900	Jan	3	10:00	St. Paul	Arrived
1900	Jan	4	10:00	St. Paul	Departed
1900	Jan	5	10:00	St. Paul	Arrived
1900	Jan	6	10:00	St. Paul	Departed
1900	Jan	7	10:00	St. Paul	Arrived
1900	Jan	8	10:00	St. Paul	Departed
1900	Jan	9	10:00	St. Paul	Arrived
1900	Jan	10	10:00	St. Paul	Departed
1900	Jan	11	10:00	St. Paul	Arrived
1900	Jan	12	10:00	St. Paul	Departed
1900	Jan	13	10:00	St. Paul	Arrived
1900	Jan	14	10:00	St. Paul	Departed
1900	Jan	15	10:00	St. Paul	Arrived
1900	Jan	16	10:00	St. Paul	Departed
1900	Jan	17	10:00	St. Paul	Arrived
1900	Jan	18	10:00	St. Paul	Departed
1900	Jan	19	10:00	St. Paul	Arrived
1900	Jan	20	10:00	St. Paul	Departed
1900	Jan	21	10:00	St. Paul	Arrived
1900	Jan	22	10:00	St. Paul	Departed
1900	Jan	23	10:00	St. Paul	Arrived
1900	Jan	24	10:00	St. Paul	Departed
1900	Jan	25	10:00	St. Paul	Arrived
1900	Jan	26	10:00	St. Paul	Departed
1900	Jan	27	10:00	St. Paul	Arrived
1900	Jan	28	10:00	St. Paul	Departed
1900	Jan	29	10:00	St. Paul	Arrived
1900	Jan	30	10:00	St. Paul	Departed
1900	Jan	31	10:00	St. Paul	Arrived

## APPENDIX II - CALCULATIONS

## A. Determination of Reserves

## 1. P/Z Values for Graphical Solution (Figure 4)

Gas Analysis: methane 97.0%; ethane 2.10%; propane 0.1%;  
oxygen 0.1%; nitrogen 0.5; carbon dioxide 0.2%; molecular  
weight 16.3; critical pressure 673 psia; critical tempera-  
ture 348°R.

Reservoir temperature 150°F<sup>\*\*</sup>; surface temperature 60°F.

Original reservoir pressure  $P = 4035$  psia as measured at the  
surface plus the pressure caused by the weight of the gas  
column in the well  $P_x$ .  $P_x$  was calculated as follows:

$$P_w = \frac{114 ZRT P_x}{M} - .5 P_x$$

where  $P_w = 4035$  psia well head pressure

$Z = .9$  (from compressibility chart for natural gas,  
using a pseudo reduced pressure  $P_r$  of  $4035 \div 673$   
 $\approx 6.0$ , and a pseudo reduced temperature  $T_r$  of  
 $565^\circ R \div 348 = 1.622$ )

$R = 10.71$  (gas constant)

$T = 565^\circ R$  (average temperature in the well)

$H = 6500$  feet (average depth)

$M = 16.3$  (molecular weight)

thus

$$4035 = \frac{(114)(.9)(10.71)(565) P_x}{(16.3)(6500)} - .5 P_x$$

$P_x = 583$  pounds per square inch.

\*All calculations by slide rule

\*\*Estimate based on 140°F. as measured for Leidy gas field

# APPENDIX II - CALCULATIONS

1. Determination of Reserves

1. 1/2 Volume for original solution (Figure 1)

Net analyzed: sodium 91.0%; oxygen 8.1%; chlorine 0.1%;  
 oxygen 0.1%; nitrogen 0.2%; carbon dioxide 0.2%; molecular  
 weight 10.3; critical pressure 27; water critical temperature  
 374°C.

Temperature 150°C; surface temperature 50°C.  
 Original reservoir pressure 1.4032 psi as measured at the  
 surface plus the pressure caused by the weight of the gas  
 column in the well 2.5 psi was calculated as follows:

$$P_w = \frac{14.7 \times 10^6}{14.7} = 10^6 \text{ psi}$$

where  $P_w$  = well head pressure

2. 2. (From compressibility chart for natural gas,  
 using a pseudo reduced pressure  $P_r$  of 0.025 ± 0.025  
 ± 0.0, and a pseudo reduced temperature  $T_r$  of  
 1.00 ± 0.01 ± 0.01)

3. 10.7 (psi constant)

4. 150°C (average temperature in the well)

5. 0.025 (psi constant)

6. 10.3 (molecular weight)

and

$$P_w = \frac{14.7 \times 10^6 \times (0.025)(10.3)(150)}{(0.025)(10.3)} = 10^6 \text{ psi}$$

7. 2.5 (psi constant for surface head)

8. 1.4032 (psi constant for surface head)

9. 1.4032 (psi constant for surface head)



Therefore, the original reservoir pressure  $P = 4035 + 583 = 4618$  pounds per square inch absolute. The corresponding compressibility factor  $Z = .97$ , using  $T_r = 610^\circ R$  (reservoir temperature)  $\div 348 = 1.75$ , and  $P_r = 4618 \div 673 = 6.85$ . The original  $P/Z = 4618 \div .97 = 4755$ .

On May 31, 1954,  $P_x$  and  $Z$  were calculated as shown above.

(See Figures 7 and 8)

$$\text{May 31, 1954 } P/Z = \frac{P}{Z} \div \frac{P_x}{Z} = \frac{2505 \div 390}{.882} = 3280$$

## 2. Analytical Method

Original gas = gas produced  $\div$  gas remaining

Considering the reservoir storage space and the reservoir temperature as remaining constant, and using the gas produced as of May 31, 1954 (Appendix III):

$$\frac{381 P_1 V}{Z_1 RT} = 89,315,450,000 \div \frac{381 P_2 V}{Z_2 RT}$$

where 381 = standard cubic feet per mole

$P_1 = 4618$  psia (original reservoir pressure)

$P_2 = 2895$  psia (May 31, 1954 reservoir pressure)

$V =$  reservoir storage space in cubic feet

$Z_1 = .97$  (compressibility factor at original reservoir pressure)

$Z_2 = .882$  (compressibility factor at May 31, 1954 reservoir pressure)

$R = 10.71$  (gas constant)

$T = 610^\circ R$  (reservoir temperature)

$$V = \frac{89,315,450,000 RT}{381(P_1/Z_1 - P_2/Z_2)}$$

$$V = \frac{(89,315,450,000)(10.71)(610)}{381(4755 - 3280)} = 1.04 \times 10^9 \text{ cubic feet}$$

$$\text{Original gas} = \frac{381 P_1 V}{Z_1 RT} = \frac{(381)(4618)(1.04 \times 10^9)}{(.97)(10.71)(610)}$$

= 289 billion standard cubic feet

Therefore, the original reservoir pressure is  $14035 \pm 1018$  pounds per square inch absolute. The corresponding compressibility factor is

$$Z = 0.91, \text{ using } T_r = 0.910 \text{ (reservoir temperature) } \div 260 = 1.15, \text{ and } P_r =$$

$$14035 \div 672 = 0.95. \text{ The original } P_r \text{ is } 14035 \div 97 = 0.152.$$

On May 21, 1954,  $P_r$  and  $Z$  were calculated as shown above.

(See Figure 1 and 2)

$$\text{May 21, 1954 } P_r = \frac{P}{P_r} = \frac{P}{0.152} = \frac{14035 \div 97}{0.152} = 3580$$

3. Analytical Method

Original gas was produced by the reservoir. Considering the reservoir storage space and the reservoir compressibility as constant, and using the gas produced on May 21, 1954 (Appendix III):

$$\frac{1}{P_r} = \frac{1}{P} = \frac{1}{3580} = 0.00027936 \div 0.91 = 0.0003059$$

where  $P_r$  is reservoir pressure and  $P$  is gas pressure

$$P_r = \text{hole rate (original reservoir pressure)}$$

$$P = 3580 \text{ psi (May 21, 1954 reservoir pressure)}$$

$$P_r = \text{reservoir storage space in cubic feet}$$

$$P = 10.71 \text{ (compressibility factor of original reservoir pressure)}$$

$$P_r = 14035 \text{ (compressibility factor of May 21, 1954 reservoir pressure)}$$

$$P = 10.71 \text{ (gas constant)}$$

$$P_r = 0.910 \text{ (reservoir temperature)}$$

$$P_r = \frac{P_r}{P} = \frac{14035}{3580} = 3.92$$

$$P_r = \frac{P_r}{P} = \frac{14035}{3580} = 3.92$$

$$P_r = \frac{P_r}{P} = \frac{14035}{3580} = 3.92$$

and  $P_r$  is reservoir pressure

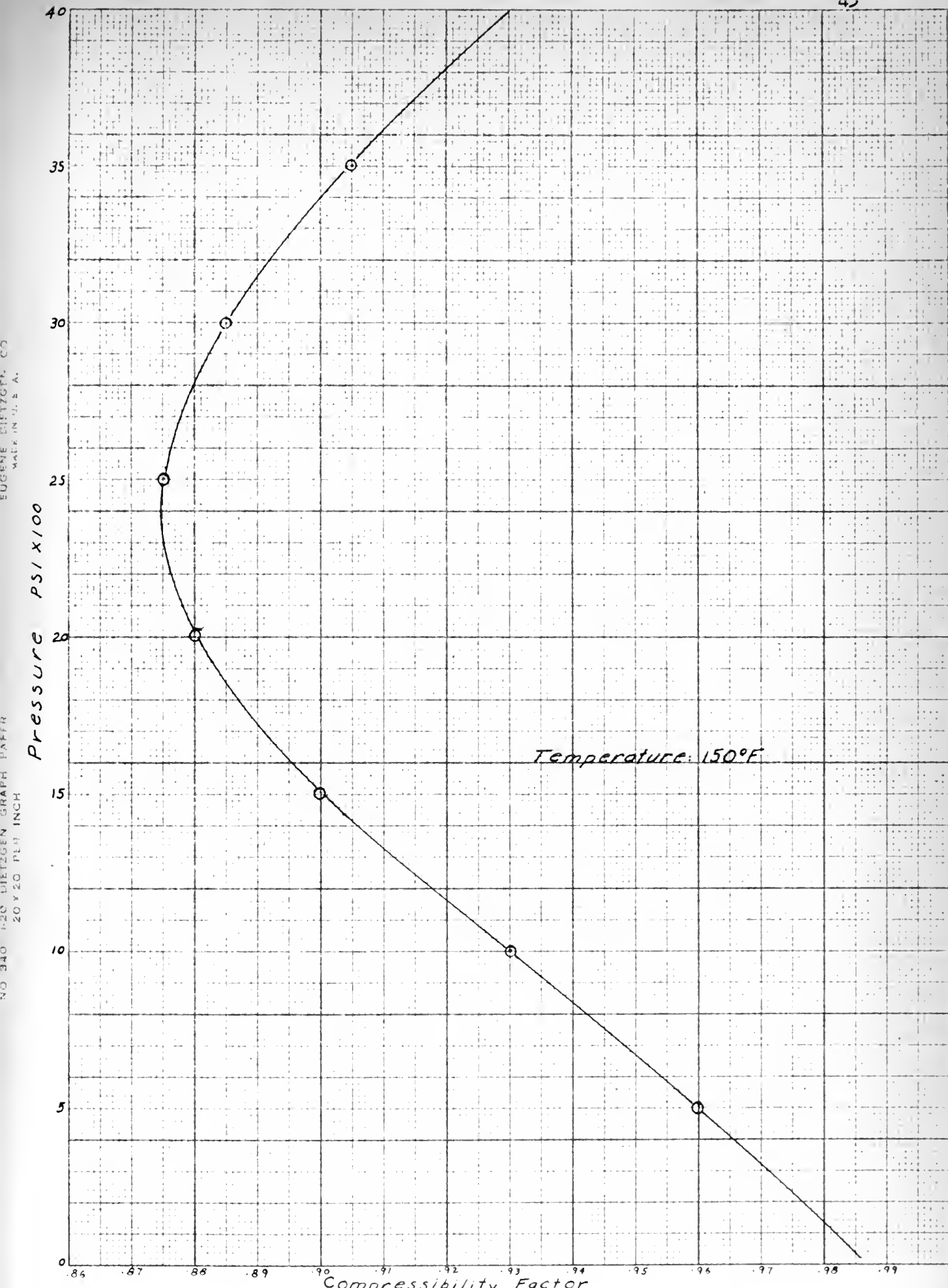


Figure 7. Compressibility Factor vs. Pressure



Well-head Pressure PSIA x 100

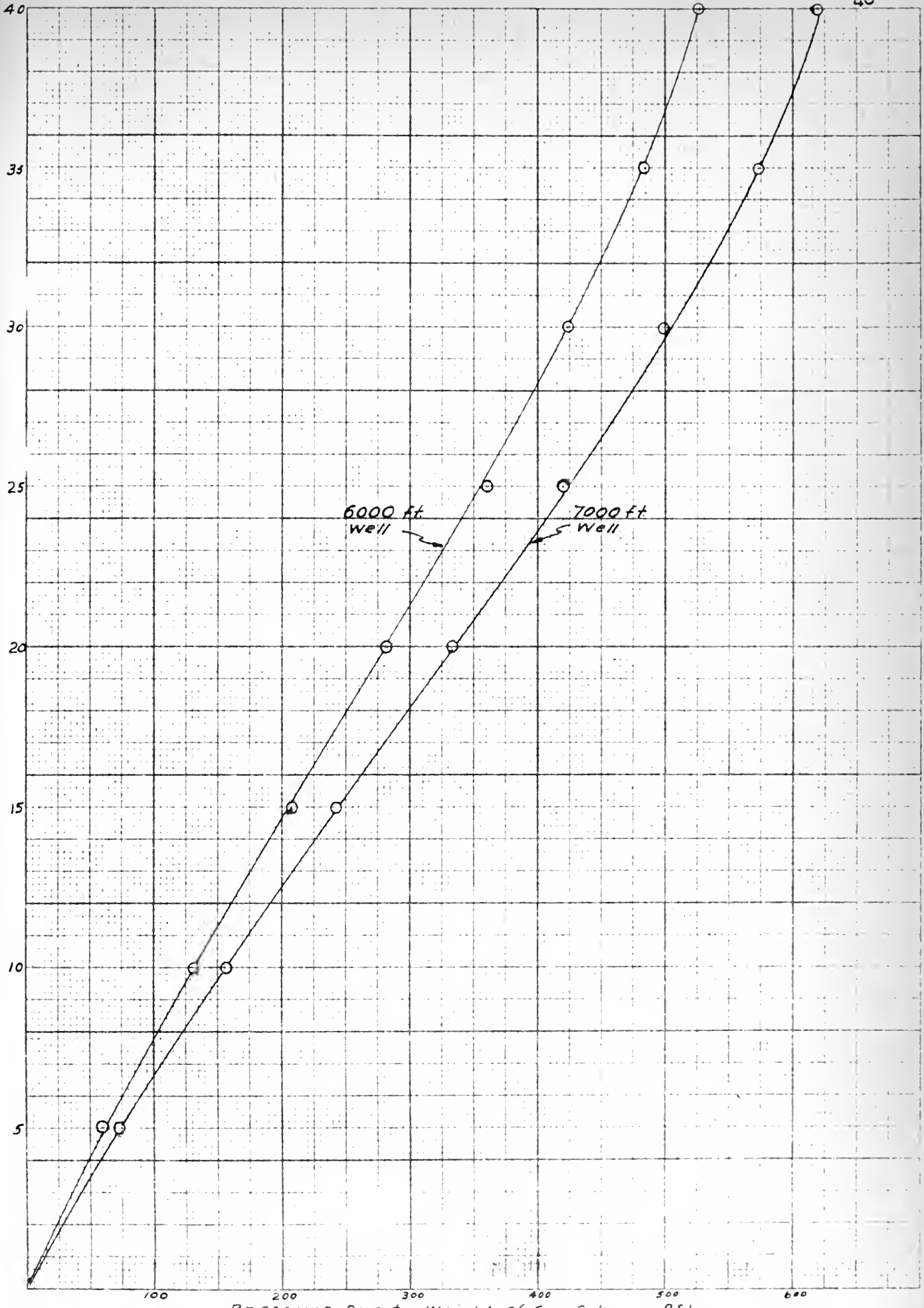


Figure 6. Pressure Due to Weight of Gas Column vs Well-head Pressure



### B. Determination of Porosity

$$\text{Porosity} = \frac{\text{pore volume}}{\text{bulk volume}}$$

Pore volume =  $1.04 \times 10^9$  cu. ft. (as shown in Appendix II, Section A, 2 on the preceding page) plus an estimated 20 per cent of the pore volume for connate water saturation.

Bulk volume = approximately 42,000 acres x 17 feet average sand thickness x 43,560 cu. ft. per acre-foot =  $31.1 \times 10^9$  cu. ft.

$$\text{Porosity} = \frac{(1.04 \times 10^9)(100)}{(31.1 \times 10^9)(1-.20)} = 4.18\%$$

### C. Determination of Permeability

The Darcy's Law radial flow equation<sup>23</sup> for viscous isothermal flow

$$Q_D = \frac{19.98 Kh (P_e^2 - P_w^2)}{P_b \mu \ln \frac{r_e}{r_w}}$$

can be rewritten to give

$$Q_s = \frac{703 Kh (P_f^2 - P_s^2)}{\mu \ln \frac{r_e}{r_w} T_f}$$

where

$Q_s$  = standard cubic feet per 24 hours

$K$  = permeability in darcies

$h$  = effective sand thickness in feet (approximately 17)

$P_f$  = reservoir pressure, psia

$P_s$  = pressure at the sand face (or flowing bottom hole pressure) psia

$r_e$  = drainage radius of the well in feet (estimated 1000)

$r_w$  = radius of the well bore in feet (.256)

# B. Determination of Porosity

$$\text{Porosity} = \frac{\text{Pore Volume}}{\text{Bulk Volume}}$$

Pore volume =  $1.00 \times 10^3$  cc. (as shown in Appendix II, Section A, 2 on the preceding page) plus an estimated 20 per cent of the pore volume for connate water saturation.  
 Bulk volume = approximately  $13,000$  cc.  $\times$  17 feet average thickness  $\times$   $13,500$  cu. ft. per acre-foot  $\times$   $31.1 \times 10^3$  cu. ft.

$$\text{Porosity} = \frac{(1.00 \times 10^3)(100)}{(31.1 \times 10^3)(1.20)} = 0.16\%$$

# C. Determination of Permeability

The core's low radial flow equation<sup>12</sup> for viscous laminar flow

$$Q = \frac{0.001127 k h (P_e - P_w)}{\mu L} \quad (1)$$

can be rewritten as

$$k = \frac{Q \mu L}{0.001127 h (P_e - P_w)} \quad (2)$$

where

- $Q$  = standard cubic feet per day
- $k$  = permeability in darcies
- $h$  = effective sand thickness in feet (approximately 17)
- $\mu$  = reservoir viscosity, cp
- $L$  = permeable sand core length for flowing bottom hole pressure (approximately 100)
- $P_e$  = pressure in the well in feet (estimated 100)
- $P_w$  = pressure in the well in feet (100)



$\mu$  = viscosity in centipoises (about .021)

$T_f$  = flowing temperature, °R (610)

In the equation  $Q = C(P_f^2 - P_s^2)^n$ , when  $n$  equals one,  $C$  is equivalent to:

Therefore,  $C$  is equivalent to:

$$C = \frac{703 Kh}{\mu \ln r_o/r_w T_f}$$

Therefore,

$$K = \frac{C \mu \ln r_o/r_w T_f}{703 h}$$

substituting:

$$K = \frac{(.456)(.021)(8.27)(610)}{(703)(17)}$$

$$K = .00405 \text{ darcy or } 4.05 \text{ millidarcies}$$

is a constant in equilibrium (about 0.01)

is a function of temperature, or (0.01)

is the equation  $\log \frac{S_1}{S_2} = \frac{H}{RT} \ln \frac{S_1}{S_2}$ , when a certain value of  $S$  is given.

For the

$$\frac{103.1}{1.1 \times 10^3} = 0.093$$

Therefore,

$$\frac{103.1}{1.1 \times 10^3} = 0.093$$

Therefore,

$$\frac{103.1}{1.1 \times 10^3} = 0.093$$

is a constant in equilibrium (about 0.01)

## APPENDIX III

Monthly and Cumulative Production  
(Thousands of Standard Cubic Feet)

<u>Date</u>	<u>Monthly</u>	<u>Cumulative</u>	
July, 1952	188,059	188,059	52
August	335,508	523,567	53
September	487,600	1,011,167	54
October	626,391	1,637,558	55
November	646,559	2,284,117	56
December	779,402	3,063,519	57
January, 1953	707,450	3,770,969	58
February	675,666	4,446,635	59
March	702,671	5,149,306	60
April	699,867	5,849,173	61
May	914,232	6,763,405	62
June	2,064,370	8,827,775	63
July	3,325,838	12,153,613	64
August	3,813,343	15,966,956	65
September	4,631,769	20,598,725	66
October	5,921,232	26,519,957	67
November	8,517,966	35,037,923	68
December	9,417,934	44,455,857	69
January, 1954	9,566,001	54,021,858	70
February	8,455,139	62,476,997	71
March	8,814,765	71,291,762	72
April	9,079,005	80,370,767	73
May	8,897,687	89,268,454	74
June	8,632,640	97,901,094	75
July	9,035,862	106,936,956	76
August	8,402,474	115,339,430	77
September	7,224,472	122,563,902	78
October	6,493,945	129,057,847	79
November	6,122,523	135,180,370	80
December	5,605,069	140,785,439	81
January, 1955	5,392,746	146,178,185	82
February	4,238,335	150,416,520	83
March	4,306,508	154,723,028	84
April	3,835,448	158,558,476	85
May	3,591,968	162,150,444	86

## DISCUSSION

(The following is a summary of the information received from the above sources.)

Year	Month	Day	Time	Location	Notes
1900	Jan	1	10:00	St. Paul	First service
1900	Jan	2	10:00	St. Paul	Second service
1900	Jan	3	10:00	St. Paul	Third service
1900	Jan	4	10:00	St. Paul	Fourth service
1900	Jan	5	10:00	St. Paul	Fifth service
1900	Jan	6	10:00	St. Paul	Sixth service
1900	Jan	7	10:00	St. Paul	Seventh service
1900	Jan	8	10:00	St. Paul	Eighth service
1900	Jan	9	10:00	St. Paul	Ninth service
1900	Jan	10	10:00	St. Paul	Tenth service
1900	Jan	11	10:00	St. Paul	Eleventh service
1900	Jan	12	10:00	St. Paul	Twelfth service
1900	Jan	13	10:00	St. Paul	Thirteenth service
1900	Jan	14	10:00	St. Paul	Fourteenth service
1900	Jan	15	10:00	St. Paul	Fifteenth service
1900	Jan	16	10:00	St. Paul	Sixteenth service
1900	Jan	17	10:00	St. Paul	Seventeenth service
1900	Jan	18	10:00	St. Paul	Eighteenth service
1900	Jan	19	10:00	St. Paul	Nineteenth service
1900	Jan	20	10:00	St. Paul	Twentieth service
1900	Jan	21	10:00	St. Paul	Twenty-first service
1900	Jan	22	10:00	St. Paul	Twenty-second service
1900	Jan	23	10:00	St. Paul	Twenty-third service
1900	Jan	24	10:00	St. Paul	Twenty-fourth service
1900	Jan	25	10:00	St. Paul	Twenty-fifth service
1900	Jan	26	10:00	St. Paul	Twenty-sixth service
1900	Jan	27	10:00	St. Paul	Twenty-seventh service
1900	Jan	28	10:00	St. Paul	Twenty-eighth service
1900	Jan	29	10:00	St. Paul	Twenty-ninth service
1900	Jan	30	10:00	St. Paul	Thirtieth service
1900	Jan	31	10:00	St. Paul	Thirty-first service

## APPENDIX IV

## Producing Wells and Dry Holes by Dates

<u>Date</u>	<u>Total No. Prod. Wells</u>	<u>Total No. Dry Holes</u>	<u>Date</u>	<u>Total No. Prod. Wells</u>	<u>Total No. Dry Holes</u>
Sept., 1951	1	-	July, 1952	53	52
October	1	-	August	75	52
November	1	-	September	91	53
December	1	1	October	107	57
January, 1952	1	1	November	127	59
February	1	4	December	144	61
March	1	7	January, 1953	161	62
April	1	9	February	175	67
May	2	15	March	187	72
June	3	22	April	201	80
July	5	28	May	217	82
August	7	31	June	233	86
September	8	33	July	243	88
October	12	37	August	247	93
November	14	39	September	253	94
December	19	40	October	260	98
January, 1953	24	40	November	265	100
February	28	40	December	269	101
March	30	44	January, 1955	272	102
April	33	45	February	276	102
May	37	47	March	277	102
June	46	51	April	277	102
			May	277	102

[illegible]

SECRET

Year	Month	Total No.	Total No.	Total No.	Total No.
1927	January	1	1	1	1
1927	February	1	1	1	1
1927	March	1	1	1	1
1927	April	1	1	1	1
1927	May	1	1	1	1
1927	June	1	1	1	1
1927	July	1	1	1	1
1927	August	1	1	1	1
1927	September	1	1	1	1
1927	October	1	1	1	1
1927	November	1	1	1	1
1927	December	1	1	1	1
1928	January	1	1	1	1
1928	February	1	1	1	1
1928	March	1	1	1	1
1928	April	1	1	1	1
1928	May	1	1	1	1
1928	June	1	1	1	1
1928	July	1	1	1	1
1928	August	1	1	1	1
1928	September	1	1	1	1
1928	October	1	1	1	1
1928	November	1	1	1	1
1928	December	1	1	1	1
1929	January	1	1	1	1
1929	February	1	1	1	1
1929	March	1	1	1	1
1929	April	1	1	1	1
1929	May	1	1	1	1
1929	June	1	1	1	1
1929	July	1	1	1	1
1929	August	1	1	1	1
1929	September	1	1	1	1
1929	October	1	1	1	1
1929	November	1	1	1	1
1929	December	1	1	1	1

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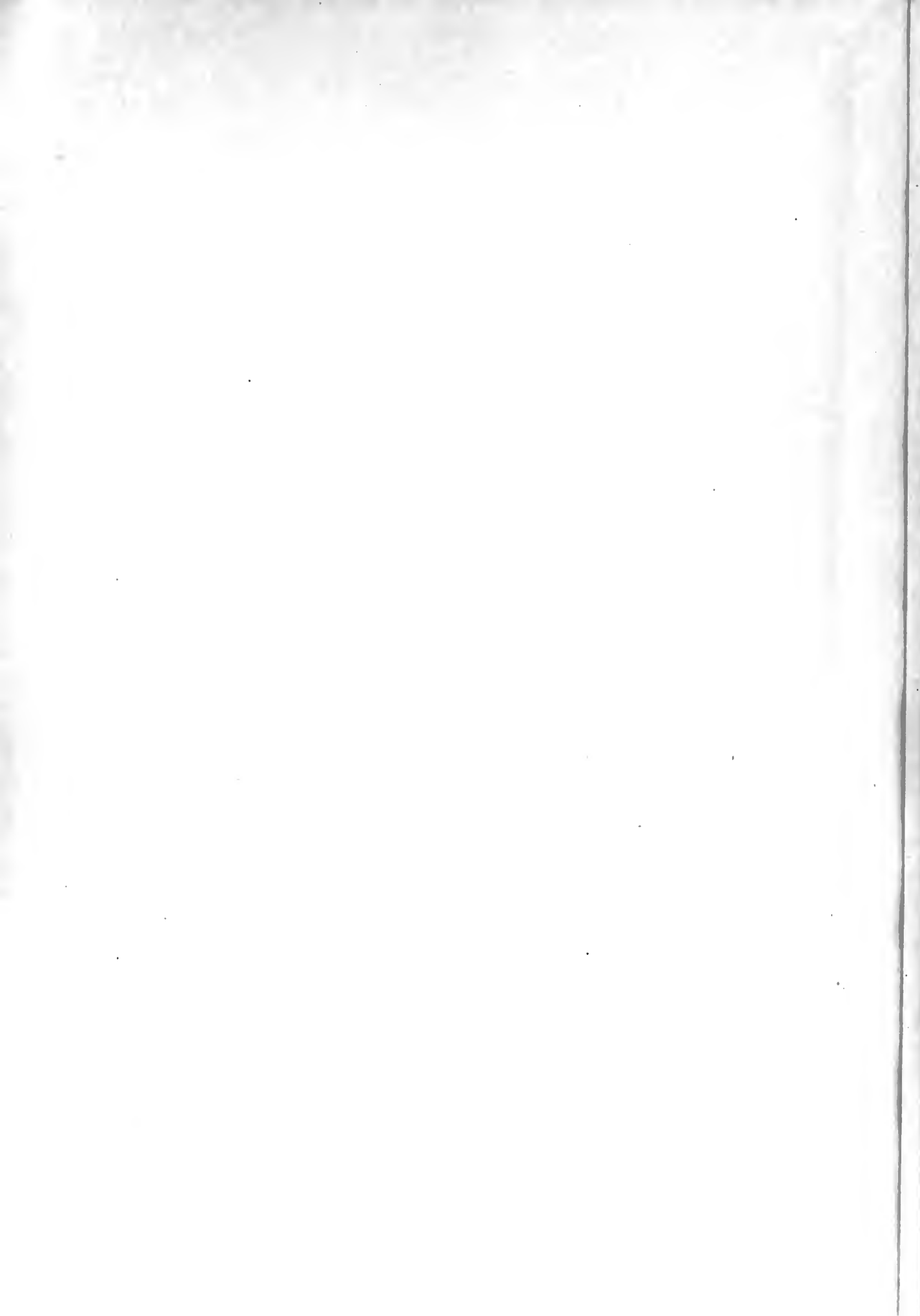
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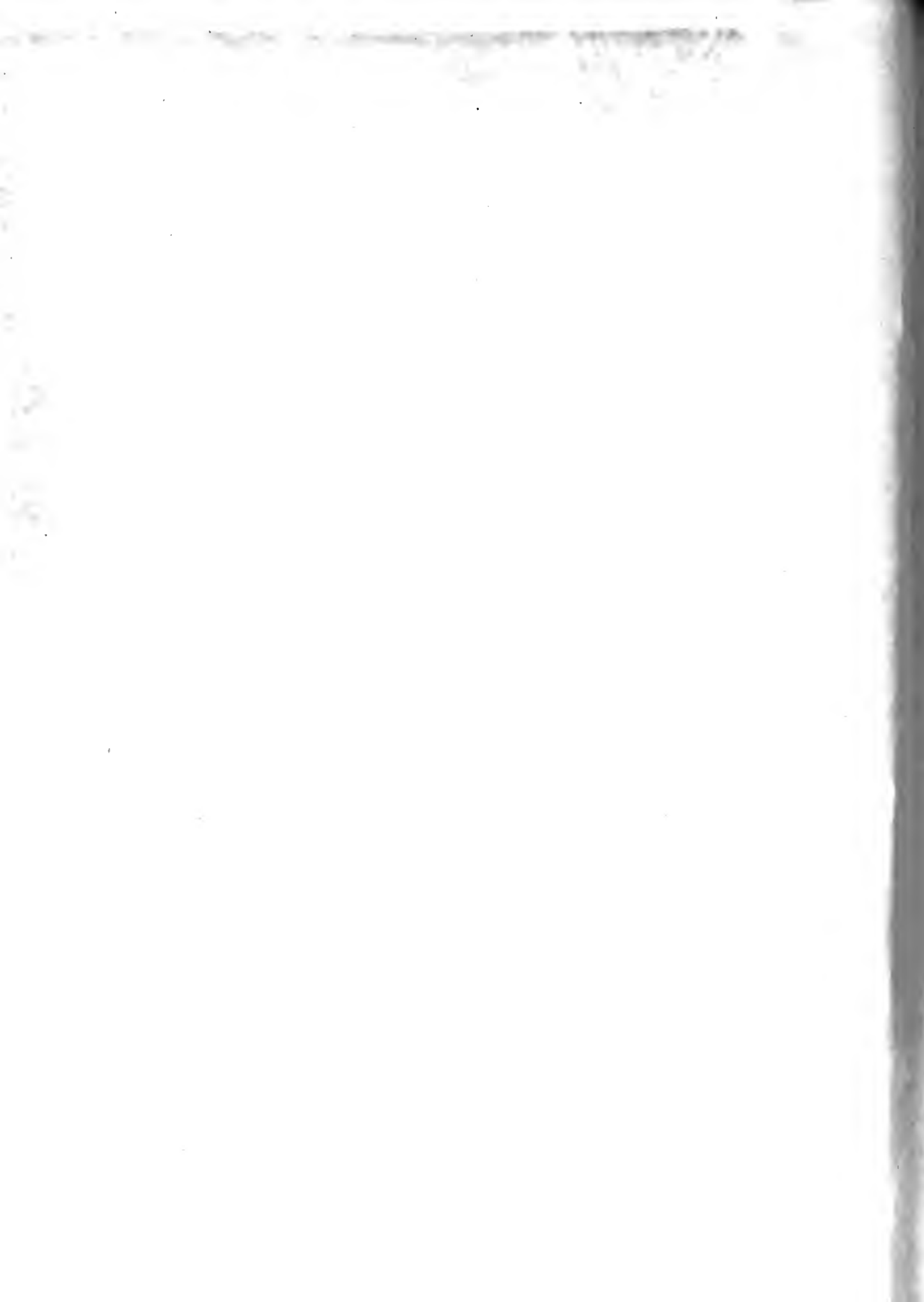














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